THE NATURE AND ORIGIN OF THE ROCKS OF THE LOWER GRIQUATOWN STAGE AND THE ASSOCIATED DEPOSITS OF AMPHIBÔLE ASBESTOS IN THE NORTHERN CAPE, WITH SPECIAL REFERENCE TO THE KOEGAS-PRIESKA AREA.

by

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ABSTRACT.

Unweathered specimens of rocks of the Lower Griquatown Stage, as well as of the associated amphibole asbestos, have only become available for investigation during the course of the past ten years. Detailed microscopic, chemical and X-ray examination of unaltered specimens obtained from the deepest mines and bore-holes showed that the rock exposed above the water-table has been altered to such a degree that conclusions regarding its origin cannot be based on examination of specimens of this rock. Not one of the existing theories explains satisfactorily the origin of the rock or of the associated amphibole asbestos, and the persistence of economic deposits of asbestos in depth has been open to doubt.

From investigations carried out in the field and in the laboratory, the writer has come to the conclusion that the banded ironstone was formed from material precipitated chemically. The nature of the material precipitated was controlled by the chemical environment in the basin of deposition. The effects of regional metamorphism are negligible and the amphibole asbestos was not formed as a result of stress set up during periods of regional folding, but crystallized directly from a colloidal precipitate of parent-material of amphibole. The fibrous habit of the amphibole asbestos is the result of crystallization of minute needles of amphibole perpendicular to an initiating surface of pre-existing magnetite. The crystallization of the amphibole asbestos took place between the period of mild Pre-Loskop and intense Post-Waterberg deformation, and the quantity of asbestos developed is often related to the gentle Pre-Loskop folding.

The writer feels that these views on the origin of the amphibole asbestos and the rocks of the Lower Griquatown Stage

offer a satisfactory explanation for the distribution of the asbestos and its fibrous habit. There is no longer any doubt as to the persistence of amphibole asbestos with increasing depth, both as regards quality and quantity, and new, completely hidden deposits have been discovered by application of the principles outlined in this thesis. This knowledge, combined with the development of suitable modern techniques of exploration, assures the asbestos industry of an adequate supply of raw material for the foreseeable future.

I. INTRODUCTION

A. GENERAL:

Crocidolite has been mined in the Cape Province since 1893, when the Cape Asbestos Company acquired surface- and mineral rights in the Koegas area. Production of amosite in the Transvaal was commenced in 1914, and in 1925 the largest mines producing this mineral, the Egnep and Amosa Mines at Penge, were also acquired by this Company.

In the early days the recovery of crocidolite in the Cape was done mainly by Coloured workers on the contract system. These independent workers removed fibre-bearing rock from hundreds of small, isolated surface-exposures. The rock adhering to the asbestos was hammered off, generally by members of the contractor's family, and the fibre "cobs" sold to the Company. These contractors were responsible for finding their own exposures of fibre, and the hundreds, possibly thousands, of small scratchings along the sides of the hills from Prieska in the south to the border of the Bechuanaland Protectorate in the north, bear testimony of their activities. With the constantly increasing demand for crocidolite, this system was gradually replaced by systematic mining methods and today the large asbestos mines in South Africa are well laid out, efficiently run organizations with all modern amenities. As production increased it became necessary to locate new deposits of crocidolite, and a geological department was formed in the Cape Asbestos Company in June 1954. Since that date the writer has been engaged in exploration for crocidolite in the Cape Province and has also spent some months in the amosite fields of the Transvaal.

For the successful prediction of the behaviour of any mineral deposits it is necessary to have a clear understanding of its mode of origin. It was thus necessary to study in detail not only the mode of occurrence, but also the genesis of amphibole asbestos in the Cape Province. This work forms the basis of the present thesis.

The problem of the origin of crocidolite has interested petrologists and mineralogists for many years. The most important papers on the subject are those by Hall (1918 and 1930), Peacock (1928) and Du Toit (1945). Over the past six years the writer has had the opportunity of studying in detail the deposits of crocidolite in the Cape Province. Much new material has become available since the days of Du Toit, and during the course of this investigation the writer has reached the conclusion that none of the existing theories on the genesis of crocidolite explains entirely the features observed in this area.

The petrology of the banded ironstone of the Lower Griquatown Stage has also not been cleared up entirely, mainly on account of the fact that specimens of fresh rock have only become available during the past ten years. The writer has examined hundreds of thin sections cut from fresh specimens obtained from various mines on the asbestos fields of the Cape Province. Owing to the extreme fineness of grain of the greater portion of the rocks of the Lower Griquatown Stage, microscopic examination had to be amplified by X-ray analysis, which was carried out at the Government Metallurgical Laboratory in Johannesburg, and at the Ceramics Unit of the Council for Scientific and Industrial Research, Pretoria.

It is the purpose of this thesis to present the characteristics of some of the occurrences of crocidolite in the Cape Province, as well as those of the rocks with which the asbestos is associated. The material presented herein represents a by no means complete study of all the aspects of the mode of occurrence and the origin of the banded ironstone and the amphibole asbestos in the Cape Province. The optical and chemical variations within mineral species and the changes associated with the metamorphism and weathering of the rocks and the asbestos have yet to be investigated in detail. Nevertheless, it is hoped that the present study will throw new light on the origin of the banded ironstone and the associated deposits of amphibole asbestos, and that it may serve as a framework for more detailed investigations in future.

B. LOCATION OF THE AREA:

In the Cape Province crocidolite is developed only as seams interbedded with the banded ironstone of the Lower Griquatown Stage, which is a member of the Pretoria Series of the Transvaal System, and exploration for crocidolite is therefore confined to this type of rock. Its distribution is shown on Plate XI, from which it can be seen that the Lower Griquatown Stage is confined to the region bounded on the west and east by meridians 22°15' east and 24°30' east respectively and on the north and south by the parallels of latitude 25°30' south and 30°00' south respectively.

During the course of his work the writer has had the opportunity of examining most of the asbestos occurrences and mines in this vast area, but as it would not have been possible to make a detailed mineralogical investigation of each, the Koegas-Prieska area was selected as being the most suitable for this purpose, not only because of the presence of the Koegas-Westerberg Mine, which is the oldest and largest crocidolite mine in the world, but also because of the excellent exposures of the rock on surface. Much additional and extremely valuable information was obtained from an extensive programme of diamond-drilling in and around this mine: a programme of magnitude unique in the fields of amphibole asbestos in South Africa.

The Koegas-Westerberg mining-area is situated on both sides of the Orange River in the Divisions of Hay and Prieska. Latitude 29°20'S and longitude 22°21'E intersect roughly in the middle of the area. The accompanying map (Plate XII) was compiled from a series of detailed maps made of the mining-area on a scale of 1:2,500, and from a more general map of the remaining area on a scale of 1:20,000, with reference to the various underground plans on a scale of 1:500.

C. DISTRIBUTION OF CROCIDOLITE IN THE CAPE PROVINCE:

In the Cape Province crocidolite is found as interbedded seams in the banded ironstone of the Lower Griquatown Stage, which is the lowest of the three divisions of the Pretoria Series in that Province. The lowermost asbestos seams are located not far above the contact of the banded ironstone and the underlying dolomitic limestone of the Dolomite Series. The distribution of the Lower Griquatown Stage is indicated on Plate XI. The banded ironstone is more resistant to weathering than either the underlying dolomitic limestone or the overlying andesitic lava and generally forms hills rising to over 1,000 feet above the surrounding country.

The Lower Griquatown Stage is exposed in a continuous belt, some 230 miles long, from about 25 miles south of Prieska to about 55 miles north of Kuruman. The stretch, known as the Asbestos Hills in the south and the Kuruman Hills in the north, represents the eastern flank of a series of shallow, doubly plunging synclines elongated in a north-south direction, and which are separated by a series of equally gentle arches, which cause repetition of outcrop of the banded ironstone up to 55 miles west of the Asbestos and the Kuruman Hills. Andesitic lava of the Middle Griquatown Stage is preserved in the troughs of the large synclines, whereas rocks of the Dolomite Series are exposed in a few places in the eroded crests of the arches. South of the Orange River the banded ironstone gives rise to the Doornberg Range. West and north of Kuruman the rocks are mostly obscured by Kalahari sand, and in a more southerly direction the Transvaal System is overlain unconformably by beds of the Matsap and Gamagara Formations. In the Postmasburg area the structure is complicated by westward-dipping, low-angle thrust-faults. From 15 miles north of Koegas to 25 miles south of Prieska, the Transvaal System is terminated abruptly by the Doornberg fault. East of a line between Griquatown and Prieska the Transvaal System is unconformably overlain by rocks of the Karroo System.

Between the point where the Kuruman Hills vanish to the north underneath a thick cover of Kalahari sand and the border of the Bechuanaland Protectorate, a distance of some 90 miles, rocks of the Lower Griquatown Stage are exposed as a series of isolated "islands" rising above the sand to heights seldom exceeding 100 feet. The most northerly crocidolite mine at Pomfret, some 30 miles south of the border of the Bechuanaland Protectorate, is situated on such an "island".

Crocidolite asbestos is developed sporadically in the banded ironstone of the Lower Griquatown Stage throughout the area underlain by these rocks, but known economic deposits of this mineral are comparatively few. The first small crocidolite workings south of the rich Pomfret Mine mentioned above lie near Heuningvlei, some forty miles south of Pomfret. Within a radius of twenty miles from Kuruman lie a number of producing mines, including Riries, Whitebank and Asbes, all of which have sizeable ore-bodies. Other mines in the area, including some now just commencing operations and others already worked out, are Bestwell, Bretby, Depression, Langley, Mansfield, Mount Vera and Newstead.

In the vicinity of Daniëlskuil and Postmasburg, some fifty miles south of Kuruman, no large mines are producing at the present moment, but several deposits, e.g. those on Schietfontein and Mimosa, have been discovered recently during the course of intensive prospecting programmes. They are now being developed and, combined with large new ore-reserves being blocked out in older mines, e.g. at Warrendale, this area will be capable of producing appreciable tonnages of crocidolite in the near future. In addition to these mines, asbestos has also been produced in the past from properties such as Hurley, Klipvlei, Crawley, Billinghurst, Grasmere, and Oudeplaats.

South of Warrendale the first producing mines are encountered in the vicinity of Prieska, about 100 miles south of Warrendale, although crocidolite has been found along the intervening strike of the banded ironstone and has been extracted in the past on various properties including Naauwpoort and Elandsfontein in the Niekerkshoop area.

Crocidolite is now being produced from various properties in the vicinity of Prieska, including Glen Allan, Buisvlei, Geduld, Erfrus, Kliphuis, Stofbakkies, and Carn Brae. Small tonnages of crocidolite have also been produced in the past from Klein Naauwte, Enkeldewilgeboom, Orange View, Naauwgekneld, Dikberg, Prieskas Poort, Asbestos Reefs, Lovedale, and other farms.

As a result of large, gentle folds, the asbestos-bearing banded ironstone is exposed on surface for some forty miles northwest of Prieska, where the Koegas Asbestos Mine, the largest single producer of crocidolite in the world, lies adjacent to the Orange River. The greater portion of the asbestos of this mine is obtained from the Westerberg Syncline, where asbestos has been mined uninterruptedly since 1893. This deposit of crocidolite is unique both because of its size and the remarkable persistency of the fibre. Crocidolite is also found on various other properties in the vicinity of Koegas, including Bultfontein, Nauga, Geelbeksdam, Pypwater, Leelykstaat, and Stilverlaat, but only the last two properties are producing at the present moment. The Blackridge Mine, now closed, lies forty miles north-northeast of Koegas.

D. THE KOEGAS-PRIESKA AREA:

1. Summary of Previous Work

The earliest accounts of the structure of what is now known as the Transvaal System in the Cape Province, were those of Burchell, Lichtenstein and Moffat, referred to by Rogers (1937 pp. 6-7 and 64-65). Stow (1874) was the first to establish the general geological succession.

Lichtenstein first noted crocidolite during his travels in South Africa in 1803 and 1806, when he collected a massive blue mineral in the Orange River valley near Prieska. Hall (1930, pp. 32 and 35) quotes an analysis of Lichtenstein's material made by Klaproth in 1815.

Rogers and Du Toit (1910) surveyed the Hay and Prieska divisions in 1904 and 1905. Their geological map of the area on a scale of 1:238,000 was published in 1910.

Hall re-examined the area in 1917 and 1918, and much information was included in his memoir on the South African asbestos deposits, the first edition of which was published in 1918. A second, revised edition was published in 1930.

No detailed geological work had been done in the Koegas area and, although short visits were paid later to this area by a number of geologists, their reports are mainly concerned with the then controversial problem of the extension and persistence of the known deposits of fibre in depth. Structural information in these reports is, in consequence, of a very general nature.

2. Topography

The Koegas area is somewhat rugged, sparsely overgrown with low bush and little grass, and contrasts strongly with the flat "inselberg" landscape found to the west and the gentle undulating surface of the Karroo east of Prieska. The bed of the Orange River is about 3,000 feet above sea-level at Koegas, and the surrounding hills rise to more than 1,000 feet above the level of the valley.

The general trend of the hills varies from north-south to northeast-southwest and they are roughly parallel to one another. The topography of the area has been controlled by the composition of the underlying rock, modified by the numerous igneous intrusions. In areas where the underlying rocks have high dips the crests of the hills are inclined to be sharp and of the cockscomb type, whereas in areas where the rocks have low dips the hills form small plateaus. A conspicuous, thick sheet of igneous rock is often responsible for minor escarpments which bound these plateaus.

The valley patterns are dependant on the disposition of the hills, and longitudinal valleys are the most conspicuous. Transverse branch-valleys, with a general northwest-southeast trend, cut across the hills at angles varying between 45° and 90°. Their directions have been determined by numerous dykes, which are roughly parallel to one another and are less resistant to weathering than the adjacent strata.

3. Rainfall and Drainage

The average annual rainfall in the Koegas area is of the order of 9 inches per year, and is confined mainly to the months of February and March, generally in the form of short, violent thunderstorms. Drainage is rapid, via the transverse and longitudinal valleys to the Orange River. The effects of the topography, climate and rainfall on the weathering of the rocks are discussed on page 17.

II GEOLOGY.

A. GENERAL STATEMENT.

The crocidolite fields of the Cape Province extend from immediately east and north of the Doornberg fault in the Koegas-Prieska area to the border of the Bechuanaland Protectorate in the north. The stratified rocks encountered in this region may be divided as follows:-

Tertiary and Recent Deposits			Sand Alluvium Gravel and scree deposits Surface-limestone
Karroo System	Dwyka Series		Tillite and shale
Waterberg System	Matsap Formation	Upper Matsap Stage.	Quartzite and grit
		Lower Matsap Stage.	Mainly andesitic lava.
Loskop System (Gamagara Formation)			Quartzite, conglomerate and shale. Basal conglomerate and quartzite.
Transvaal System	Pretoria Series	Upper Griquatown Stage	Banded ironstone and jasper, chert, limestone, shale, quartzite and lava.
		Middle Griquatown Stage	Andesitic lava with interbedded tuff, chert and jasper.
		Lower Griquatown Stage	Banded ironstone and jasper, mudstone, shale, quartzite, limestone and tillite.
	Dolomite Series		Dolomitic limestone, chert and shale.
	Black Reef Series		Quartzite, shale and conglomerate.
Igneous intrusions			Kimberlite pipes Dolerite dykes Diabase related to the Ongeluk volcanics.

The thesis is concerned primarily with the rocks of the

Lower Griquatown Stage and the associated deposits of amphibole asbestos.

B. THE TRANSVAAL SYSTEM.

Attention should be drawn to an apparent inconsistency concerning the contact between the Dolomite and the Pretoria Series. In the Transvaal an interbedded succession of asbestos-bearing ironstone is present near the top of the Dolomite Series. As this succession of banded ironstone lies below the Bevet's conglomerate, which is taken as the base of the Pretoria Series, the ironstone is included in the Dolomite Series. However, in the northwestern Cape Province the Bevet's conglomerate is absent and the banded ironstone, which here succeeds the Dolomite conformably, is included in the Lower Griquatown Stage. In the Transvaal, therefore, the amphibole asbestos is found in the upper portion of the Dolomite Series, whereas in the Cape it is found in the lower portion of the succeeding Pretoria Series.

A similar inconsistency exists regarding the upper boundary of the Lower Griquatown Stage. In the Transvaal a band of tillite is found just below the base of the Ongeluk Volcanics of the Daspoort Stage. In the Northwestern Cape the equivalent of the Daspoort Stage, the Middle Griquatown Stage, consists almost entirely of andesitic lava with occasional thin interbedded bands of jasper. A tillite, up to 100 feet thick in places, is present below the lava, and is separated from it by up to 50 feet of shale or mudstone. It is therefore found in exactly the same position as in the Transvaal, but in the Cape the base of the andesitic lava is considered to mark the upper boundary of the Lower Griquatown Stage, so that the tillite is included in this Stage. Both the lower and upper contacts of the Lower Griquatown Stage do not therefore correspond strictly with those of the Timeball Hill Stage in the Transvaal with which it is correlated.

Marked lithological differences exist between rocks of the Lower Griquatown Stage in the Cape Province and the corresponding rocks of the Pretoria Series in the Transvaal, with which they are correlated. The banded ironstone and jasper, which are so prominent in the Cape, are not developed in the type-area around Pretoria, where the hills are built of resistant quartzite and the valleys underlain by soft shale.

1. The Dolomite Series.

The Dolomite Series, formerly referred to as the Campbell Rand Series [a name still employed by Du Toit (1954)] is lithologically nearly identical with its counterpart in the Transvaal. The upper portion of this Series is exposed only in the northwestern and southwestern portions of the Koegas mining-area, where it is succeeded conformably by a white shale, 50 feet thick, which is in turn followed by the banded ironstone of the Lower Griquatown Stage. The portion of the Dolomite Series exposed consists of fine-grained, blue-grey dolomitic limestone with intercalated bands of chert which become more frequent towards the top of the Series.

2. The Pretoria Series.

In the northwestern Cape Province the Pretoria Series is subdivided into three stages: the Lower Griquatown Stage, the Middle Griquatown or Ongeluk Stage, and the Upper Griquatown Stage.

The latter stage is known only to the west of Postmasburg, some 65 miles N.N.W. of the Koegas area, and was not examined. The Ongeluk lava is preserved in the troughs of the large synclines described earlier, but was not included in the present investigation, which was confined to the Lower Griquatown Stage.

The Lower Griquatown Stage.

a. General Statement:

The distribution of the Lower Griquatown Stage in the Cape Province is illustrated on Plate XI, from which it is seen that the rocks of this Stage are present in a series of interconnected, shallow, doubly-plunging synclines elongated in a north-south direction. The most important of these are the Dimoten Syncline, the Ongeluk-Witwater Syncline, and the Abramsdam Syncline. Truter et al (1938), Visser (1944) and Boardman and Visser (1958) have recently described portions of the Dimoten and the Ongeluk-Witwater Syncline. The stratigraphical succession described in detail in this thesis is that of the Abramsdam Syncline, of which the Koegas-Prieska area forms a part, but the mineralogical relationships are similar in the same rock-types found in the other synclines.

During the course of prospecting-operations carried out by the Cape Asbestos Company during the past six years between Prieska in the south and the Bechuanaland border in the north, it was necessary to establish the stratigraphical succession in various localities along this stretch of over 300 miles. It was found that the rocks in the Prieska area could be correlated with great accuracy with those in the Koegas-Westerberg area, both of which lie within the boundary of the Abramsdam syncline; likewise, the succession near Hurley, approximately 20 miles north of Daniëlskuil, is remarkably similar to that found approximately 20 miles northwest of Kuruman. Both these areas lie within the boundary of the Dimoten syncline. Similar relationships hold within the other large synclines, the largest of which is the Ongeluk-Witwater syncline. However, when the rocks belonging to certain synclines are compared with those belonging to some of the other synclines, detailed correlation becomes difficult. Conspicuous markers in one syncline are absent in the next, and the total thickness of the Lower Griquatown Stage, remarkably constant in one syncline, is vastly different in the next. Possibly the most striking difference is the presence of a succession of at least 2,500 feet of shale and mudstone (the latter carrying abundant clastic grains of quartz and other minerals) in the Abramsdam syncline, which is completely absent in the Kuruman area surveyed by the writer, and their absence is confirmed by the work of Visser (1944) and others. Further reference to this will be made in Chapter III.

Where the Lower Griquatown Stage crosses the border of the Union of South Africa in the north, to continue in a wide arc through the Bechuanaland Protectorate until it again enters the Union near Lobatsi, the total thickness of the Stage is less than 1000 feet, but the outcrops are mainly obscured by a thick cover of Kalahari sand and as yet no detailed subdivision has been made of the succession in this area.

In the Kuruman and Griquatown areas the Lower Griquatown Stage has been subdivided into three zones: a Banded Ironstone Zone at the bottom, a Banded Jasper Zone in the middle, and a Tillite Zone at the top. Truter et al (1938, pp. 18-19) give the thickness of these zones in the Kuruman and Postmasburg regions as 1000, 1500 and 50 feet respectively, and state that the asbestos horizon lies about 100 feet above the contact with the dolomite. In the areas mentioned above there is a complete transition between the Dolomite Series and the Pretoria Series. Near the top of the Dolomite Series thin bands of jasper and magnetite become increasingly frequent, whereas near the bottom of the Pretoria Series bands of dolomitic limestone are still present.

In the Koegas-Prieska area the Lower Griquatown Stage attains a thickness of about 5000 feet (i.e. twice its thickness in the Kuruman, Griquatown and Postmasburg areas), and there are two major differences in the stratigraphical succession: firstly, a Transition-zone consisting of white shale is present between the Dolomite Series and the Banded Ironstone Zone, and secondly, the Jasper Zone recognised in the areas farther to the north is replaced by the Mudstone Zone.

The Banded Ironstone Zone in the Koegas-Prieska area is subdivided as follows: a basic intrusive sill, approximately 300 feet thick, is present about 1400 feet above the Dolomite Series. The rocks between the Transition-zone and the sill are known as the Lower Banded Ironstone Beds, whereas those immediately above the sill are known as the Upper Banded Ironstone Beds, which are followed by the Westerberg Beds.

The Mudstone Zone is subdivided into the Lower Shale Beds, the Lower Mudstone Beds, the Chert Layer, the Upper Shale Beds, and the Upper Mudstone Beds.

The succession of beds encountered in the Prieska-Koegas area is therefore as follows:-

	Ongeluk volcanics		Middle Griquatown Stage	PRETORIA SERIES	TRANSVAAL SYSTEM
<u>Thickness in feet</u>					
50	Tillite Beds	Tillite Zone	Lower Griquatown Stage		
1300+	Upper Mudstone Beds	Mudstone Zone			
300+	Upper Shale Beds				
20	Chert Layer with Upper Asbestos Horizon				
400	Lower Mudstone Beds				
500	Lower Shale Beds				
300	Westerberg Beds with Westerberg Asbestos Horizon	Banded Ironstone Zone			
400	Upper Banded Ironstone Beds with Prieskaite Horizon				
300	Sill				
1300+	Lower Banded Ironstone Beds with Intermediate Asbestos Horizon and Lower Asbestos Horizon				
50	White Shale	Transition-zone			
	Dolomite Limestone and Chert			DOLOMITE SERIES	

The asbestos-bearing banded ironstone of the Lower Griquatown Stage is extremely susceptible to alteration under the normal agencies of weathering and has undergone extensive leaching and oxidation down to a depth of 250 feet below surface. Du Toit (1945, pp. 165-168) established three zones of weathering. The Fresh Zone is present below the permanent water-table, which generally lies between 50 and 200 feet below surface. In this zone the rock is finely laminated, hard, compact and dark blue to black with occasional pale grey bands. Above the water-table the rock is generally soft and yellow-brown as a result of the oxidation and leaching of the constituent minerals: this represents the Leached Zone. Near surface these rocks have become hardened owing to secondary silicification and carbonation. This zone is known as the Silicified Zone and generally forms only a thin crust near the surface. It may even be completely absent in areas of high rainfall, but may extend vertically to depths of over 100 feet in areas of low rainfall, e.g. at Klein Naauwte and some other farms in the Prieska district. Fortunately, the asbestos is more resistant to weathering than the enclosing rock and often persists right to surface with little obvious deterioration in quality. In fact, until about 1950 all the amphibole asbestos produced was obtained from the Leached and Silicified Zones, known collectively as the Weathered Zone. Under extreme weathering all types of amphibole asbestos are oxidized and hydrated to a soft yellow powder which resembles ochre.

When a specimen of a specific layer of banded ironstone obtained from surface is compared with its unweathered equivalent as exposed in the deeper underground workings, the intensity of oxidation, hydration and silicification is most striking. A detailed study of the processes of weathering is beyond the scope of this work, and only a brief description of the weathered rocks is given.

The descriptions of the banded ironstone given by Peacock (1928) and in the publications of the Geological Survey of the Union of South Africa, including the two most recent publications [the explanations of Sheet 173, Oliphants Hoek (1938) and Sheet 175, Griquatown (1958)] are those of the highly altered superficial or near-surface variety. Du Toit (1945, pp. 163-168) describes specimens taken at deeper levels, but completely unaltered strata had not been exposed in any workings in the Cape asbestos fields at the time when these specimens were taken, so that, in fact, no description of the unaltered rocks of the Lower Griquatown Stage has been published to date.

In the course of his examination of unaltered specimens of banded ironstone the writer has found that they contain minerals which have not been recognized in the equivalent rocks exposed on surface owing to the extreme alteration the rocks have undergone in the Weathered Zone. Some of the minerals present in the unaltered banded ironstone appear to be unique in South Africa.

Owing to the extreme fineness of grain of the bulk of the rocks of the Lower Griquatown Stage, microscopic examinations had to be amplified by X-ray analysis. Although some minerals could be removed from the rock specimens to facilitate the analysis and identification of the remaining minerals, it was practically impossible to separate mixtures of certain minerals into absolutely pure fractions. A similar difficulty was encountered by Gruner (1944b, p. 365) in the course of examination of rocks of the Huronian System (Lower Proterozoic). However, it was possible to remove the carbonates from the rock powder by the method used by Gruner (idem), whereby the specimen is finely powdered and heated in about 200 c.c. of nearly boiling water, to which is added slightly more hydrochloric acid than is estimated to dissolve the carbonate. As soon as effervescence stops, the solution is diluted to twice its volume with cold water. The powder that settles is washed by repeated decantation. Gruner found that this treatment could be carried out without injury to the silicates. Before the above treatment was carried out, magnetite was removed with a hand-magnet.

To simplify the description of the mineral assemblages in the various rock-types found in the Abramsdam Syncline, the minerals characteristic of the unaltered banded ironstone are detailed below:-

Chert: The term "chert", as used throughout the Lake Superior region, is applied to the fine-grained, non-clastic quartz that typically forms layers in the iron-bearing formation. All of it is crystalline [James (1951) p. 255]. Microscopic examination of the "chert" in the Lower Griquatown Stage showed that it is in all respects identical with that described from the Lake Superior region. In hand-specimen its appearance is typically that of ordinary chert. Although the above definition of the term "chert" differs from the standard definitions as given by Dana (1932, p. 473) and Rice (1949, p. 71), the term is retained in this thesis on account of its long usage both in South Africa and in the United States of America. Under the microscope chert from the banded ironstone resembles a fine-grained quartzite, but this term is reserved for rocks composed of cemented or metamorphosed clastic grains of quartz.

Carbonate: Carbonate is frequently encountered in the fresh rocks of the Lower Griquatown Stage, either interlocking with other minerals, or as isolated euhedral or subhedral crystals lying in a fine-grained matrix of chert or silicates. The ratio of $CaCO_3$ to $MgCO_3$ to $FeCO_3$ in the carbonate crystals varies considerably, as shown by the chemical analyses in Table I. The optical properties of the carbonate vary with the chemical composition. Where the indices of refraction could be measured, nE and nO were equal to or greater than 1.554 and 1.739 respectively. From Table I it is also seen that the composition of the carbonate does not appear to be related to the stratigraphical position from which the specimens were obtained.

Minnesotaite: Ever since the discovery of economic deposits of iron ore in the Mesabi Range, State of Michigan, U.S.A., petrographers have observed a mineral in the western part of the Biwabic Formation of the Huronian System which they called an amphibole, or sometimes specifically grunerite. Gruner (1944b, pp. 363-372) established that this mineral is not an amphibole, but a variety of talc, now known as minnesotaite. It is now recognized as a major constituent of many iron-beari rocks in the Lake Superior region. Grunerite is present in these rocks only in the garnet and staurolite zones of metamorphism. Du Toit (1954, p. 158) states that the slaty sediments of the Lower Griquatown Stage "contain much chlorite and amphiboles such as crocidolite, cummingtonite and grunerite". The writer suspects that the last two mineral species actually refer to minnesotaite, which he found in abundance and widely distributed in the Lower Griquatown Stage.

Gruner states that minnesotaite has only been found in microscopic needles and plates, the needles radiated or in sheaves. Under a magnification of 300 diameters minnesotaite appeared as felt-like yellowish green masses. The minnesotaite found in the Lower Griquatown Stage matches this description exactly (Plate 7).

TABLE I.

CHEMICAL ANALYSES OF CARBONATE.

(Analysts: Central Laboratory, The Cape Asbestos Company)

Sample Number	%CO_2	%CaO	%MgO	Total Fe expressed as %FeO	%$CaCO_3$ (from %CaO)	%$MgCO_3$ (from %MgO)	%$FeCO_3$ (from remaining CO_2)	Remaining Fe expressed as:		Ratio of $CaCO_3$: $MgCO_3$: $FeCO_3$	Sample Number
								FeO	Fe_3O_4		
C 1	1.46	n.d.	n.d.	n.d.	-	-	-	-	-	-	C 1
C 2	11.64	1.69	2.00	23.66	3.02	4.18	21.42	10.37	11.14	0.72 : 1 : 2.48	C 2
C 3	13.05	0.63	2.09	25.47	1.12	4.37	27.09	8.66	9.30	0.26 : 1 : 6.20	C 3
C 4	17.20	0.61	1.88	26.88	1.09	3.93	38.66	2.89	3.10	0.28 : 1 : 9.84	C 4
C 5	5.05	1.55	0.40	6.84	2.77	0.84	8.93	1.30	1.40	3.30 : 1 : 10.63	C 5
C 6	18.00	1.80	1.57	23.79	3.21	3.28	39.21	-.54	-.58	0.98 : 1 : 11.95	C 6
C 7	13.05	2.45	1.39	18.22	4.37	2.91	25.32	2.51	2.70	1.50 : 1 : 0.87	C 7
C 8	7.42	7.74	0.33	3.33	13.81	0.69	2.61	1.71	1.84	20.02 : 1 : 3.78	C 8
C 9	0.57	n.d.	n.d.	n.d.	-	-	-	-	-	-	C 9
C10	11.49	0.59	1.89	19.89	1.05	3.95	23.64	5.22	5.61	0.27 : 1 : 5.98	C10
C11	4.86	4.25	0.88	5.40	7.58	1.84	1.50	4.47	4.80	4.12 : 1 : 0.82	C11
C12	7.02	1.79	1.59	13.43	3.19	3.33	10.22	7.09	7.62	0.96 : 1 : 3.07	C12
C13	21.58	1.13	1.86	31.51	2.02	3.89	49.17	1.00	1.07	0.52 : 1 : 12.64	C13

C 1 : Upper Mudstone Beds, from outcrop, Koegas.
C 2 : Lower Mudstone Beds, Bore-hole W13, Westerberg.
C 3 : Near contact, Lower Mudstone and Lower Shale Beds, Bore-hole W13, Westerberg.
C 4 : Lower Sahle Beds, Bore-hole W13, Westerberg.
C 5 : Lower Shale Beds, Bore-hole W2, Westerberg.
C 6 to C 8: Westerberg Asbestos Horizon, Bore-hole W2, Westerberg.
C 9 : Upper Banded Ironstone Beds, Bore-hole W2, Westerberg.
C10 : Lower Banded Ironstone Beds, Intermediate Asbestos Horizon, Geduld Mine.
C11 : Lower Banded Ironstone Beds, 300 ft. below Sill, Bore-hole W2, Westerberg.
C12 : Lower Banded Ironstone Beds, 1000 ft. below C11, Bore-hole W2, Westerberg.
C13 : Lower Banded Ironstone Beds, Lower Asbestos Horizon, Buisvlei Mine.

The mineral is pale yellow to pale green and some crystals exhibit faint pleochroism. The optical properties are difficult to determine on account of the extreme fineness of grain. It was found that the occasional crystals large enough to permit optical measurements are biaxial, negative, with a small optic angle. The mineral has a perfect basal cleavage, with the acute bisectrix normal thereto. The crystals show positive elongation and parallel extinction. Birefringence is fairly high, and the refractive indices are nX : 1.58 and nZ : 1.62. A typical X-ray pattern for a rock containing an appreciable quantity of minnesotaite is given in Table II.

TABLE II.

X-RAY DIFFRACTION-PATTERN OF MINNESOTAITE-BEARING ROCK

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

MINNESOTAITE-BEARING ROCK. Lower Shale Beds, Westerberg		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.
9.6	100			9.1	50	9.53	100
8.4	45			8.4	100		
4.89	10			4.89	30		
4.80	5					4.77	10
4.51	10			4.50	70		
4.25	10	4.26	35				
3.60	10					3.50	10
3.42	10			3.41	50		
3.34	45	3.34	100				
3.19	20					3.18	50
3.11	20			3.10	100		
2.99	5			2.99	10		
2.79	10					2.75	5B
2.72	25			2.71	100		
2.66	5					2.65	5
2.60	20			2.60	50		
2.54	25			2.53	50	2.52	20
2.46	10	2.46	12			2.40	10
2.32	10	2.28	12	2.31	60	2.31	5
2.21	5					2.22	10
2.18	10			2.17	60		
2.13	5	2.13	9			2.11	5
						2.01	10
						1.92	10
1.83	10	1.82	17				
1.66	10	1.67	7	1.65	50	1.66	10
1.61	10			1.61	30		
1.60	10					1.60	10B
1.57	5					1.57	10

(X-ray diffraction-pattern measured in the Government Metallurgical Laboratory, Johannesburg, and at the Ceramics Unit of the Council for Scientific and Industrial Research, Pretoria.)

Stilpnomelane: Gruner (1944a, pp. 291-298) reviewed the compositional and structural information on stilpnomelane, and suggested that its structure is derived from that of talc or biotite. Hutton's calculations (1938, pp. 172-206) also suggested a mineral related to talc or mica, but apparently stilpnomelane contains more water than these minerals. Winchell (1951, pp. 390-391) states that the formula of stilpnomelane is quite uncertain, but that it is chemically related to chlorite, although optically very similar to biotite, from which it differs in having a less perfect basal cleavage (and a poor cleavage normal thereto), a strong yellow tint (X), no mottled effect on extinction, more brittle flakes, and a less definite X-ray pattern.

Under the microscope the marked pleochroism of stilpnomelane is characteristic, but it varies with the ratio of ferrous iron to ferric iron in the molecule. Stilpnomelane with a low content of ferric iron is pleochroic from pale yellow to deep green, whereas stilpnomelane with a high content of ferric iron is pleochroic from yellow to dark reddish brown, and is often opaque in thin sections. The mineral is uniaxial, negative (or biaxial, negative with a 2V of 0°). The refractive indices increase with an increasing content of ferric iron (nZ varies from 1.58 to 1.74). The optical properties are thus very much the same as those of hydrobiotite.

An X-ray diffraction-pattern of a specimen of banded ironstone containing an appreciable quantity of stilpnomelane is given in Table III, in which a typical pattern for biotite is included for comparison. Apparently the reflection normal to the good cleavage is variable, as it is in the hydrobiotite and vermiculite minerals, owing to additional water held rather loosely between the talc or mica sheets.

TABLE III.

X-RAY DIFFRACTION-PATTERN OF STILPNOMELANE-BEARING ROCK

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

STILPNOMELANE-BEARING Lower Banded Ironstone Beds Westerberg		QUARTZ A.S.T.M. Card 5-0490		CROCIDOLITE Vermaas (1952 p. 225)		STILPNOMELANE Gruner (1937 p. 919)		BIOTITE A.S.T.M. Card 2-0045	
dA	Int.	dA	Int.	dA	Int.	dA	Int.	dA	Int.
						13.0	60		
10.1	100			9.1	50	11.9	100	10.1	100
8.4	15			8.4	100				
4.53	10			4.50	70			4.58	20
4.25	20	4.26	35						
4.13	10					4.04	50		
3.34	75	3.34	100	3.41	50	3.34	10	3.36	100
3.10	10			3.10	100	3.03	40	3.15	20
								2.91	20
2.83	5					2.82	10		
2.79	20			2.71	100	2.70	20		
2.67	40			2.60	50			2.65	80
2.53	15			2.53	50	2.56	40	2.51	40
2.49	35	2.46	12					2.45	80
		2.28	12	2.31	60	2.34	30	2.28	20
2.21	15			2.17	60			2.18	80
2.13	10	2.13	9			2.11	20		
2.02	10							2.00	80
								1.91	20
1.82	10	1.82	17						
1.73	10							1.75	20
1.70	10			1.65	50			1.67	80
1.57	15					1.58	30		
						1.56	30		
1.51	20	1.54	15	1.51	70	1.52	20	1.54	80

(X-ray diffraction-pattern measured in the Government Metallurgical Laboratory, Johannesburg, and at the Ceramics Unit of the Council for Scientific and Industrial Research, Pretoria.)

Gruner (1944b, p. 371) proposed the following formulae for minnesotaite, stilpnomelane and greenalite:

Minnesotaite:

$$(OH)_{5.5}\ (Fe'',Mg)_{5.5}\ (Si,Al,Fe''')_8\ O_{18.5}$$

Stilpnomelane:

$$(K,Na,Ca)_{0-1}\ (OH)_4\ (Fe'',\ Mg,Al,Fe''')_{7-8}\ Si_8\ O_{23-24}.\ 2\text{-}4\ H_2O$$

Greenalite:

$$(OH)_{12}\ (Fe'',\ Mg)_9\ Fe'''_2\ Si_8\ O_{22}\ .2\ H_2O$$

Greenalite was not found in any of the samples from the Koegas-Prieska area examined under the microscope, nor was its presence detected by X-rays. It is also absent in many areas of the Lake Superior Region, (according to James, 1954, p. 266) . There is an increase in SiO_2 and a decrease in total H_2O from greenalite to minnesotaite. All three contain MgO in appreciable quantities, but only stilpnomelane contains an appreciable quantity of Al_2O_3. The ratio of Fe'' to Fe''' varies considerably in all three. Greenalite has a structure similar to that of serpentine. Stilpnomelane has a unique structure which approximates that of mica or chlorite without, however, being a mixture of the two. The structure of minnesotaite is similar to that of talc.

Chlorite: Chlorite is present as a very fine-grained greenish mass, with low birefringence. Occasional weakly pleochroic grains are visible and some small grains with anomalous blue interference-colours are present. The refractive index is difficult to determine on account of the extreme fineness of grain, but the average refractive index is generally of the order of 1.65. The chlorite is probably an iron-rich variety (thuringite or aphrosiderite) or a mixture of more than one type of chlorite.

Riebeckite: In the unmetamorphosed rocks of the Lower Griquatown Stage, riebeckite is present in two forms: slender needles up to 0.2 mm. long but seldom more than 0.005 mm. wide, which are orientated at random or radiate from a core of magnetite; and, secondly, riebeckite is found as lath-shaped crystals or sheaf-like aggregates. Basal sections exhibiting the characteristic amphibole cleavages are seldom seen, except where bands containing riebeckite or crocidolite have recrystallized under thermal metamorphism adjacent to igneous intrusions. Although riebeckite is a strongly pleochroic mineral, pleochroism is hardly noticed in the extremely slender needles, and in massive riebeckite-rocks the lath-shaped crystals are usually very small and orientated at random in sheaf-like aggregates, so that the general effect is that of a bright blue, non-pleochroic mass.

Crocidolite: The term "crocidolite" is used exclusively for typical cross-fibre asbestos with a composition identical to that of riebeckite. The individual fibres are so fine that, even under magnifications of up to 32,000 by means of an electron-microscope, the fibre still appears as bundles. The individual fibres are elongated parallel to their c-axes in the direction of the fibre axes, the individual crystals or bundles of crystals being orientated parallel to one another, but otherwise there is no preferred orientation of the crystals or bundles of crystals, and consequently the optical properties of individual crystals cannot be determined. The average refractive index for vibrations parallel to the fibre axes is about 1.70. The fibres are length-fast as a rule, but length-slow bundles have been noticed, and Frankel (1953, p. 78) reports length-slow fibre from some mines in the Kuruman district. Pleochroism is strong: the fibres are indigo-blue when parallel to the direction of vibration of the polariser, and a delicate lilac colour when perpendicular thereto.

On the asbestos fields a single seam of asbestos is referred to either as a "seam", or, more generally, a "band" of fibre. A group of seams that can be mined together as a unit is referred to as a "reef". This term has been taken over from the Witwatersrand goldfields and, although technically incorrect, it is retained both in the gold- and asbestos-mining industry on account of its long usage. The normal distance from the top of the highest asbestos seam to the bottom of the lowest asbestos seam in any reef is referred to as the "channel-width", and the normal distance between the top and the bottom of a stope is called the "stoping width". Channel-width and stoping width are measured in inches. The total fibre present in a reef is expressed as inches of fibre, or as a percentage. In mines of the Cape Asbestos Group, crocidolite seams in which the length of the fibre is less than ⅛" are disregarded for evaluation purposes, and in the amosite mines this minimum length is increased to ¼". A group of reefs found close to one another, but separated from one another by layers, of varying thickness, of barren rock, is called a "horizon". A horizon occupies a specific stratigraphical position, generally has a normal thickness of between 100 and 200 feet, and consists of up to ten separate reefs, each one of which may contain up to twenty single bands of fibre longer than ⅛", and up to one hundred thinner bands.

Actinolite: No crystals of actinolite large enough for microscopic identification were found in the unmetamorphosed rocks, but a green asbestos fibre with a composition similar to that of actinolite is present in the banded ironstone. Associated with this fibre are thin bands of cryptocrystalline, pale green material containing small, disseminated crystals of magnetite. This pale green material is therefore probably actinolite. It also seems probable that fine laths or needles of actinolite are more generally present in the banded ironstone, but they would be so intimately associated with the other silicates, which they resemble very closely, that it will be impossible to separate them for analysis. Actinolite could not be identified with certainty in any of the samples of which X-ray examination was carried out.

Prieskaite: Developed in the Upper Banded Ironstone Beds is a horizon of asbestos, which is pale green, soft and silky when fresh, and greyish green when partly weathered. When completely oxidised on surface this fibre is indistinguishable from completely oxidized crocidolite (griqualandite). Chemical analysis of this fibre (Table XIV, page 159) showed that it has a composition similar to that of actinolite. The physical and chemical properties of this fibre are discussed more fully in Chaper IV.

In view of the marked differences in the physical properties, mode of occurrence, and origin of this fibre compared with those of the amphibole actinolite and the material generally referred to as "actinolite asbestos", the writer proposes the name "Prieskaite" for this fibre, as it is found as interbedded seams in banded ironstone only in the Prieska District. This conforms with the established practice of referring to the fibrous form of riebeckite as "crocodolite", and to the fibrous form of grunerite as "amosite". It will also eliminate incorrect and confusing descriptions of the fibre, such as "leached crocidolite" or "crocidolite of inferior quality".

Magnetite: Magnetite is the only primary iron oxide found in unweathered specimens of the Lower Griquatown Stage. It is usually present as euhedral or subhedral crystals, either in bands or disseminated through the rock. On weathering it is changed to minerals like martite, hematite, limonite and goethite.

Pyrite: Well crystallized pyrite is a common accessory mineral in the lowest portion of the Lower Banded Ironstone Beds. Crystals up to 2.0 cm. across are disseminated through these banded ironstones, or, more often, are found in well defined bands in the same manner as magnetite. Layers of pyrite are common in the Lower Asbestos Horizon, and are especially noticable in unweathered rocks, e.g. those recently exposed in the Buisvlei, Kliphuis and Stofbakkies Mines in the Prieska area.

Metamorphic Minerals: Metamorphic minerals, e.g. biotite, grunerite, garnet and pyroxene are not present in the unmetamorphosed rocks of the Koegas-Prieska area. The local development of some metamorphic minerals in sedimentary rocks immediately adjacent to igneous intrusions in the Koegas area is described on page 117. It may be mentioned in passing that these minerals are present in the asbestos-bearing banded ironstones in the Transvaal that have undergone thermal metamorphism as a result of the intrusion of the Bushveld Igneous Complex, e.g. at the Penge Amosite Mine.

Minerals formed as a result of weathering: Du Toit (1945, pp. 163 to 165, and 1954 pp. 157 to 159) commented upon the truly fantastic difference in appearance between the weathered and unweathered equivalents of the banded ironstone of the Pretoria Series. So great are the differences between these rocks that a separate system of correlation has to be used when dealing with each variety. True unweathered rock has only been exposed to some extent in underground workings during the past ten years, and it is now clear that the differences are even greater than supposed by Du Toit. The mineralogical changes that take place during weathering of the banded ironstone and the formation of completely new minerals like nontronite, is a complete study on its own and beyond the scope of this thesis, except for such changes that take place with the weathering of asbestos and the economic significance of these changes.

b. Detailed Geology of the Koegas-Prieska Area.

The solid geology of the Koegas-Prieska area consists of the banded ironstone, jasper, arenaceous shale, and mudstone belonging to the Lower Griquatown Stage of the Pretoria Series, which follows conformably on the dolomitic limestone and chert of the Dolomite Series, but is separated from the Series by a thin transition-zone of white shale. The topmost portion of the Lower Griquatown Stage, the Tillite Zone, and the andesitic lava of the Ongeluk Stage are not present within the boundaries of the Koegas-Westerberg mining-area, but are exposed on the farms immediately to the east of Koegas. In the mining-area the rock-beds are folded and faulted, with numerous igneous intrusions up to 300 feet thick. The folds range in breadth from millimetres to tens of kilometres. Faults are present in which the vertical displacement varies from a microscopically small amount to more than 6,000 feet.

The detailed subdivision of the Lower Griquatown Stage has been given on page 16; the lithological details are given below.

i. The Transition-zone. In the Danielskuil-Kuruman area there is a complete transition from the Dolomite Series to the Pretoria Series. Near the top of the Dolomite Series thin bands of jasper and magnetite become increasingly frequent, whereas near the base of the Pretoria Series bands of dolomitic limestone are still present.

However, in the Koegas-Prieska area there is a persistent layer of white shale, up to 50 feet thick, between the Dolomite Series and the Pretoria Series. As this shale is less resistant to weathering than the overlying banded ironstone it is generally obscured under scree and gravel derived from the banded ironstone, but it is well exposed in the dry watercourse leading to the Orange River near the homestead on Buisvlei, 14 miles by road northwest of Prieska. It has also been partly exposed near the surface in asbestos workings on Nauga and Stilverlaat, near Koegas.

The rock is fine-grained, generally off-white, and soft. Bedding planes are not very well developed, but banding is emphasized by occasional red and black bands, these colours being caused by iron oxides and graphite as impurities.

Under the microscope the white shale is extremely fine-grained. Under high magnification minute colourless spots, with low relief and weak birefringence, may be seen in a matrix of a fine scaly or fibrous mineral or minerals with distinct relief and medium to high birefringence.

TABLE IV.

X-RAY DIFFRACTION-PATTERN OF WHITE SHALE.

(Co radiation. Only strongest lines given)

WHITE SHALE Buisvlei		QUARTZ A.S.T.M. Card 5-0490		MUSCOVITE A.S.T.M. Card 6-0263		KAOLINITE A.S.T.M. Card 6-0221		CHLORITE A.S.T.M. Card 2-0028	
dA	Int.	dA	Int.	dA	Int.	dA	Int.	dA	Int.
14.3	10							13.8	100
10.1	15			10.0	95				
7.1	25					7.18	100	7.0	80
4.98	5			4.97	31				
4.73	10							4.68	80
4.61	3								
4.49	5			4.47	21	4.48	80B		
4.26	25	4.26	35						
3.76	5			3.88	14				
				3.73	17				
3.54	15					3.58	100+	3.53	80
3.48	10	3.49	22						
3.34	100	3.34	100	3.34	23				
				3.32	100				
3.25	20			3.20	28				
2.99	5			2.99	34				
2.91	4			2.86	24				
2.80	3			2.79	21			2.83	60
2.60	5			2.60	16			2.65	50
2.57	10			2.57	54	2.565	80	2.55	60
						2.502	80		
2.46	10	2.46	12	2.47	8				
2.41	3			2.40	10			2.40	60B
2.39	5			2.38	27	2.386	80		
2.33	1					2.341	90		
2.28	5	2.28	12						
2.24	3	2.24	6	2.25	9			2.24	5
				2.24	4				
2.16	4			2.15	15				
2.13	5	2.13	9	2.13	21				
2.01	5							2.02	40
1.98	5	1.98	6	1.99	46	1.989	40B		
1.82	10	1.82	17						

(X-ray diffraction-pattern measured in the Government Metallurgical Laboratory, Johannesburg, and at the Ceramics Unit of the Council for Scientific and Industrial Research, Pretoria.)

X-ray examination of the white shale showed that it consists of quartz, mica (muscovite) and kaolinite, probably with a small amount of chlorite (Table IV). After heating a sample to 590°C for 30 minutes, the line at 7.1A was no longer present, thus confirming the presence of kaolinite. No carbonate could be found in the white shale, and no efforvessence was detected when a finely ground sample was treated with cold or hot hydrochloric acid.

ii. The Banded Ironstone Zone. A characteristic feature of the rocks of the Banded Ironstone Zone, which serves to distinguish them from the rocks of the Mudstone Zone, is their high content of magnetite. In many places a compass needle held four feet above the ground will swing through 180 degrees when moved a horizontal distance of as little as three feet. In some areas the compass of a light aircraft flying about 1000 feet above the ground will rotate through 360 degrees two or three times within the time of a few minutes.

The rocks belonging to the Banded Ironstone Zone are resistant to weathering, and generally form hills rising up to 1000 feet above the surrounding valleys. They build the longest range of hills in the Cape Province. South of the Orange River it is known as the Doornberg Range, in the southern part of Griqualand West as the Asbestos Hills and in the northern part as the Kuruman Hills. The total length of the range is over 200 miles.

The sedimentary rocks of the Banded Ironstone Zone in the Koegas-Prieska area are subdivided into the Banded Ironstone Beds and the Westerberg Beds. The Banded Ironstone Beds are of the order of 2,000 feet thick. A sill of basic intrusive rock which is about 300 feet thick, is found some 400 feet below the top of these beds.

The rocks above and below this sill are referred to as the Upper and Lower Banded Ironstone Beds respectively, as shown on page 16. Although this subdivision is useful in the field, the rocks of the Lower and Upper Banded Ironstone Beds are practically indistinguisable from each other. In the lithological description that follows they are treated as a unit.

The Banded Ironstone Beds. The rocks of the Banded Ironstone Beds consist of finely banded ferruginous and siliceous shale with intercalated, thin bands of yellow, brown and red jasper, and, more confined to certain zones, electric-blue to green bands of massive riebeckite which pass into a soft yellow rock where extensively weathered. They vary in colour from a pale ochre-yellow through red, purple and brown to extremely dark brown and black, according to the degrees of oxidation and hydration of the ferruginous constituents, and the ratio of ferruginous to siliceous components. Thin, black bands of nearly pure magnetite are abundant. Colour changes are sharp and clearly defined instead of being gradational. The width of individual bands varies from a fraction of a millimetre to a few centimetres, the average width being of the order of five millimetres.

In the Upper Banded Ironstone Beds and the topmost portion of the Lower Banded Ironstone Beds the bands generally appear straight or mildly warped to the naked eye, but microscopic examination usually reveals minute irregular undulations of the contact between adjacent bands. The banding becomes more irregular towards the base of the beds where bands are often not continuous, but pinch out completely, to reappear as flat lenses a little farther on, and zones of highly contorted and puckered bands are frequently encountered. The puckering is often most irregular, as shown by the photograph of a piece of drill-core on Plate I(a)3.

Occurrences of dolomitic limestone in the Banded Ironstone Zone are worthy of special mention. Two varieties are present: Firstly, a blue-grey variety, indistinguishable from the dolomitic limestone of the Dolomite Series, which may be found in any stratigraphical position. It is found as interbedded lenses, seldom more than three feet thick and with little lateral extension: generally less than twelve feet.

The second variety, usually ferruginous, is more unusual. An occurrence on Koegas was described by Du Toit (1945, pp. 165 and 195). He mentioned the interdigitational relationship between this lenticular body of sideritic dolomite and the normal shale, and stressed the fact that in one spot their mutual boundary is knife-sharp and crosses the stratification at right angles. A detailed study of these occurrences revealed that they were invariably associated with faults striking nearly parallel to the strike of the banded ironstone. The ferruginous, dolomitic limestone is found intermittently either on one or both sides of these faults and is clearly a secondary product caused by selective leaching of the banded ironstone adjacent to the faults and replacement by dolomitic material obtained from the unweathered strata.

Microscopic examination of unaltered samples of the Lower Banded Ironstone Beds obtained from drill-cores up to 3,000 feet below surface, showed that they consist of alternating bands of pure chert, magnetite, stilpnomelane, minnesotaite, riebeckite, and carbonate, and bands consisting of mixtures of these minerals in which any one mineral may predominate. The fact that the contacts between the individual bands are always sharp, and that the mineralogical composition changes completely from one band to the next, but remains constant in any one band, is of great significance, especially when the origin of the rock is considered. In the Upper Banded Ironstone Beds layers of chert and stilpnomelane are less frequent than in the Lower Banded Ironstone Beds.

The bands of pure chert consist of well-interlocking grains of clear quartz which show no effect of strain and no apparent preferred orientation. In the upper portion of the Lower Banded Ironstone Beds, the average diamater of the quartz grains is of the order of 0.05 mm., and there is a progressive increase in grain size with depth, so that in samples obtained from low down in the succession the quartz grains have an average diameter of the order of 0.08 mm. However, most of the chert bands contain variable amounts of minute, slender, green-blue needles up to 0.2 mm. long, but seldom more than 0.005 mm. wide, and orientated at random. Some of the larger needles show a pleochroism identical with that of riebeckite, but, for the greater part, the needles are too fine for pleochroism to be noticable.

A green cross-fibre asbestos with a chemical composition approaching that of actinolite is developed roughly in the middle of the Upper Banded Ironstone Beds. Consequently one may suspect that some of the minute needles observed in the chert bands could have compositions similar to amphiboles other than riebeckite. A sample from a band of chert containing a large number of fine needles was submitted to the Geological Survey of the Union of South Africa in 1958, which confirmed (Report D.449/58) that the needles are amphibole, "probably belonging to the riebeckite-crocidolite series".

Many chert bands contain disseminated, euhedral grains of magnetite with an average grain size of 0.07 mm. Where amphibole needles are present in addition to the magnetite, the longer needles invariably radiate from the magnetite crystals, as shown on Plate VIII (a). Where a band of magnetite crystals lies adjacent to a chert band, or between two chert bands that contain amphibole needles, many needles have grown from the magnetite band more or less normal to the bedding plane, as illustrated on Plates VIII (b) and (c). It is therefore clear that the magnetite, both disseminated and in layers, formed earlier than the amphibole needles, and that the amphibole needles grew preferentially from an initiating surface of magnetite where this was available.

Some chert bands have a speckled appearance in hand-specimen as a result of the presence of fairly large rhombs of carbonate with major diagonals of up to 0.6 mm. In thin section many of these rhombs show an extremely high relief, but on rotation of the microscope stage they become practically invisible as the refractive index for the extraordinary ray is approximately equal to that for the ordinary ray of quartz. A feature of these rhombs is that many of them contain, generally in the centre of the crystal, crystals of quartz identical with those in the chert bands, and which contain all the accessory minerals that are present in the chert band in which they lie [Plate VI (a)]. Where amphibole needles are present in the chert, they are also present in the core of quartz crystals within the carbonate crystals, but they generally do not penetrate the carbonate crystals.

In the Banded Ironstone Zone bands consisting entirely of carbonate are rare, but the quantity of carbonate in a chert band may increase to a point where carbonate becomes the dominant mineral, and the crystals lose their euhedral outlines and have a closely interlocking texture. In the Mudstone Zone the carbonate is generally cryptocrystalline to microcrystalline and semi-opaque.

Chert bands are present that do not appear speckled in hand-specimen, but are distinctly speckled under the microscope. Under high magnification it is seen that this appearance is caused by the presence of minute laths or needles of minnesotaite, and sometimes stilpnomelane, which surround the individual grains of quartz, but do not penetrate them as do amphibole needles that may be present. If rhombs of carbonate are also present in a chert band, they are also surrounded, but not penetrated, by minnesotaite or, more rarely, stilpnomelane.

Bands consisting entirely of crystals of magnetite are rare. The bands of magnetite generally contain a small amount of quartz. Associated with this quartz are all the minerals present in the chert bands described above.

Stilpnomelane is abundant in the Lower Banded Ironstone Beds. In a hand-specimen of the unaltered rock the dark brown bands are clearly visible and markedly different from the bands of black, metallic magnetite. The mineral grains are extremely small and generally orientated at random, so that the bands appear dark olive-brown to semi-opaque with little visible pleochroism. Magnetite crystals are often present in varying amounts in bands of stilpnomelane, and in most bands grains of quartz or carbonate are also present. Small laths or needles of minnesotaite and riebeckite may also be present in varying amounts.

Bands of pure riebeckite are not uncommon. Very thin bands are present throughout the Banded Ironstone Beds, and on certain horizons they become more numerous and thicker until layers of pure riebeckite of up to three feet thick are developed. In the thicker layers the riebeckite is in the form of densely matted, small laths. As they are generally orientated at random the effect under the microscope is that of a dense, non-pleochroic mass, in strong contrast with the bands of perfectly orientated needles of riebeckite which make up the seams of crocidolite on the various asbestos horizons.

In some of the thinner layers of nearly pure riebeckite, the laths and needles of this mineral show clear preferred orientation, generally parallel or at a very small angle to the bedding planes. In hand-specimen these bands show some resemblance to fibres of crocidolite which are distinctly inclined to the bedding planes, and they are often referred to as "slip-fibre". On closer examination it is found that the material is brittle and completely unlike the soft, silky fibres of crocidolite. Microscopic examination showed that the individual crystals of riebeckite in these thin bands are many hundreds of times as wide as the individual fibres of crocidolite. Similar material is frequently found along small faults through massive riebeckite-rock, or in shear-zones. It would therefore appear that this type of parallel orientation of riebeckite laths or needles is due not to natural growth of crystals normal to an initiating surface as described earlier, but rather to rearrangement or recrystallization as a result of compressional or tensional stress in the rock after it had been partly lithified at least. This process can therefore take place at a later stage in the history of the rock, and may even be fairly recent.

Two crocidolite horizons are developed in the Lower Banded Ironstone Beds. The Lower Asbestos Horizon is found near the base of these beds, the lowest asbestos seam lying about 50 feet above the zone of White Shale. The Lower Asbestos Horizon contains up to ten reefs over a normal distance of over 200 feet. This is the best known asbestos horizon in the Cape asbestos fields, and is present over the entire stretch of banded ironstone from 25 miles south of Prieska to where it crosses the border of the Bechuanaland Protectorate in the north. All the mines in the Prieska area, with the exception of the Geduld Mine, extract asbestos from the Lower Asbestos Horizon.

In the immediate vicinity of the Koegas-Westerberg mining-area the Lower Asbestos Horizon has been eliminated by the Doornberg fault, but it is sporadically developed along the fault-scarp north of the Orange River on the farms Schalksdrift, Pypwater, Leelykstaat and Stilverlaat. South of the Orange River the westernmost exposure of the Lower Horizon is on Portion 13 of the farm Rietfontein, from where it continues, interrupted and displaced by various faults, to the southernmost exposures of fibre 30 miles south of Prieska. Owing to faulting, complex folding and highly variable dips, a clear exposure of the complete horizon is seldom seen. As a result, the very numerous scattered local exposures of one or more reefs of the Lower Horizon have never been correlated with any degree of certainty. On each small mine, each reef has its own local name: the most economical reef invariably being called the Main Reef. The other reefs may have names of other mines or farms in the district, but these are, more often than not, based on personal whims of the miners rather than definite geological correlations.

At this stage attention should be drawn to the many confusing inconsistencies in the nomenclature of the asbestos fields. There is, for instance, no reason to suppose that the so-called "Kliphuis Reef" on Klein Naauwte is actually the most important reef worked at the Kliphuis Mine: in fact, it appears unlikely. Similarly, it would be incorrect to assume that the Enkelde Wilgeboom

Mine is on Enkelde Wilgeboom or that the Nauga Mine is on Nauga. For no apparent reason, both these mines derive their names from the adjacent farms.

On Klein Naauwte the banded ironstone gives rise to a large flat plateau, cut by deep, narrow ravines. The largest, Malgas Kloof, runs approximately southwest until it joins the Orange River not far south of the Naauwte boundary. A smaller ravine, Klein Malgas Kloof, running approximately west, joins Malgas Kloof about 700 yards from the Orange River. In both Klein Malgas and Malgas Kloofs the Lower Horizon is beautifully exposed. Here ten separate reefs can be identified over a normal width of approximately 200 feet.

Most of them have been opened up on Klein Naauwte by adits, up to 300 feet long, but at no point was the Fresh Zone reached. The quantity of fibre in each reef varies, and although various reefs may contain the same total amount of fibre in bands longer than ⅛", one reef may contain only a few bands of long (i.e. 1" plus) fibre whereas other reefs are composed of numerous bands of short fibre. As at all the other mines which extract fibre from the Lower Horizon, each reef has to be judged on its own merit, with the current demand for each grade of fibre clearly in mind.

A characteristic feature of the Lower Asbestos Horizon is its extreme patchiness with regard to the development of economical deposits of asbestos. Fibre in payable quantities is developed only in small areas which are roughly circular or elliptical in plan, and which seldom exceed one thousand feet in diameter or along their major axes. Such areas of greater concentration of fibre in a reef are called "pockets". It is not unusual, especially in the Kuruman area, to find that each of the various reefs have developed "pockets" with approximately the same dimensions, one on top of the other. Such superimposed areas of greater concentration of fibre are generally associated with open folds, either synclines or anticlines. In areas where folding is poorly developed or absent, superimposed "pockets" are the exception rather than the rule. The relation of folding to the increased development of fibre in a reef of asbestos is discussed in Chapter IV.

About 200 feet below the thick basic sill a second horizon of crocidolite is developed in the Prieska area, but it is absent in the Koegas-Westerberg area. This horizon has been named the Intermediate Asbestos Horizon, and it is from this that fibre is extracted at the Geduld Mine, some 30 miles by road northwest of Prieska.

The Intermediate Horizon consists of at least three reefs over a normal distance of approximately 150 feet. A characteristic feature of the asbestos fibre from this horizon at the Geduld Mine is its acute inclination, generally between 45° and 20° to the bedding planes. The fibre is found in a soft, finely laminated, blue shale which breaks easily.

Near the main Geduld Reef there is a narrow band of pale grey fibre. This band is generally found on its own, but samples of fibre have been taken from it, in which one half is pale grey and the other half blue, reminding one of fibre with a similar appearance from the Malips River area in the Transvaal where the so-called "doublets" and "triplets" of crocidolite and amosite are found. These have been described by Hall (1930, p. 212), Du Toit (1945, pp. 186 and 187), and Vermaas (1952, p. 214 and Plate XXXII, Fig. 2). The composition of the pale grey fibre from Geduld Mine is still uncertain, and it does not appear to be of any economic significance.

Examination of unweathered samples of the country-rock from the Geduld Mine showed that it is identical in all respects with the rock from this stratigraphical position intersected by diamond-drill in the Westerberg Valley at Koegas.

It is unfortunate that no bore-hole in the Koegas area was drilled deep enough to intersect the Lower Asbestos Horizon. Samples of unweathered rock were therefore obtained from mines near Prieska, but no complete exposure has been made across the strata in the Fresh Zone. In general the rocks have the same mineralogical composition as those exposed in bore-holes in the Koegas area, with this difference that, at least in the lower reefs of the Lower Asbestos Horizon, pyrite is present, often in appreciable quantities, in addition to magnetite which is still found in bands and disseminated through the rock in exactly the same manner as in the higher bands of the Banded Ironstone Zone. The pyrite is present as euhedral crystals, up to 2 cms. across. They may be disseminated through the rock, but are more often confined to well defined bands in the same manner as magnetite. As a rule, bands of pyrite are separated from bands of magnetite by one or more bands of quartz, carbonate and/or silicate.

In the Buisvlei Mine a striking rock lies between bands of crocidolite and massive riebeckite. It consists of alternating thin bands of magnetite and wider pale brownish yellow bands, some of which contain disseminated pyrite. Microscopic examination showed that these bands consist of euhedral and subhedral crystals of carbonate set in a matrix of quartz and minnesotaite, with some laths and needles of riebeckite [Plates V (a) and (b)].

The X-ray diffraction-pattern of the rock, after removal of the carbonate and magnetite, shows the same lines as those of the rock shown in Table II, but the intensities of the lines are different owing to the different proportions of the three minerals present. This brownish yellow rock contains spherical blobs of minute crystals of matted riebeckite. A typical blob is illustrated in Plate IV (c). This blob of riebeckite lies in a brownish yellow band and the upper and lower edges of the blob are partly imbedded in bands of magnetite which have thickened on either side of the riebeckite blob. Around the latter, and separating it from the surrounding magnetite is a thin mantle of brownish yellow material identical with that in the normal bands. The magnetite bands immediately above and below the riebeckite blob are slightly bulged where they go around it, but the banding of magnetite bands farther above and below the blob is undisturbed.

Some of these brownish yellow bands, when followed along the strike, gradually become richer in riebeckite at the expense of the carbonate, quartz and minnesotaite, and the associated bands of magnetite and crocidolite also give way to massive riebeckite. Such changes in facies over a fairly short distance along the strike are not common in the banded ironstone, in which the individual bands, however thin, can be followed for long distances. Some bands, not more than two millimetres thick, have been traced on surface at Koegas for a distance of over twenty miles along the strike. Nevertheless, local changes in facies, such as that described above on Buisvlei, do indicate that whilst conditions were favourable for the deposition of one suite of minerals in one particular area, a slight change of these conditions in an adjacent area resulted in a different mineral or suite of minerals being deposited there at the same time and in the same stratigraphical position.

Veins consisting predominantly of quartz and carbonate attain widths of several feet and cut through the banded ironstone roughly normal to the bedding [Plate I (a) 2]. Small veinlets of quartz, carbonate and riebeckite are present in the chert bands. (Plate VII). These veinlets are seldom more than 3 mm. long and 0.3 mm. wide, and peter out in both directions. The veins cut through all the bands present in the rock. The material in the veins is identical with that in the normal sedimentary bands, but is always more coarsely crystalline. These veins represent contraction-cracks in the rock, formed at an early stage in its history, which were filled by material derived from the adjacent, then incompletely lithified sedimentary layers.

Roughly in the middle of the Upper Banded Ironstone Beds lies the Prieskaite Horizon. The asbestos fibre developed on this horizon is pale green when fresh, and grey-green when weathered. Its chemical composition is quite different from that of crocidolite and amosite, but closely resembles that of actinolite. The properties of this type of amphibole asbestos are treated in more detail in Chapter IV.

The Westerberg Beds. The Westerberg Beds are magnetic, have a thickness of 300 feet, and weather somewhat more easily than the underlying Banded Ironstone Beds. On surface the Westerberg Beds can often be recognized at a distance by their more distinctly yellow colour. Two or three persistent intrusive sills are present in these beds in the Koegas-Westerberg area, and in some localities many additional lenticular, thin sills are present. In a few places the sills cut through the sedimentary beds at low angles when followed over distances of five miles or so. As a rule, only the lower 120 feet of the

Westerberg Beds carry crocidolite. A persistent sill, about 40 feet thick, lies approximately 35 feet above the highest asbestos seam in the Westerberg Valley, where it is known as the Marker Sill. The distance is reduced to as little as five feet above the same reef on Koegas and Hounslow, north of the Orange River. On some parts of these farms further seams of asbestos are developed above the Marker Sill. The distribution of the crocidolite bands in the Westerberg Horizon is shown in a typical section in Table V. Some thin bands of crocidolite are also sporadically developed in the waste partings between the principal reefs.

Immediately above the asbestos-bearing strata lies a succession of approximately 100 feet of shale which weathers to a characteristic dark chocolate-brown colour. This shale is magnetic in places and is somewhat more resistant to weathering than the asbestos-bearing succession, so that it occasionally forms small foot-hills, especially in folded areas, at the base of the main range of hills formed by the Upper Banded Ironstone Beds.

Microscopic examination of samples of the Westerberg Beds showed that their mineralogical composition is much the same as that of the Upper Banded Ironstone Beds. Bands of chert are virtually absent and there is little stilpnomelane. Bands of carbonate are common, but euhedral crystals are rare, the crystals of carbonate having a closely interlocking texture. The rock is finely banded. In unaltered samples the bands are black, pale green, white and blue as a result of the predominance in them of magnetite, minnesotaite, carbonate and riebeckite respectively, whereas bands of intermediate colours are present owing to mixtures of these minerals in single bands.

TABLE V.

DISTRIBUTION OF CROCIDOLITE IN THE WESTERBERG ASBESTOS HORIZON.

WASTE PARTING (Feet)	REEF	REEF CHANNEL-WIDTH (Inches)	AVERAGE NUMBER OF FIBRE BANDS OVER ⅛"	AVERAGE FIBRE LENGTH (Inches)	MAXIMUM FIBRE LENGTH (Inches)
	INNER	10" - 40"	5 - 15	⅛" - ¾"	2 "
6 '					
	MAIN	6" - 48"	5 - 15	⅛" - 2¼"	4 "
4 '					
	BOTTOM MAIN	24" - 40"	5 - 15	⅛" - 1 "	1 "
8½'					
	VISSER	48" - 82"	5 - 18	⅛" - ½"	1¼"
4½'					
	BOTTOM VISSER	6" - 12"	3 - 8	⅛" - ¼"	¾"
35 '					
	INTERMEDIATE	5" - 32"	2 - 10	⅛" - ¼"	½"
12 '					
	OUTER	9" - 48"	5 - 18	⅛" - ¾"	1 "
7 '					
	SECOND OUTER	3" - 27"	2 - 6	⅛" - ½"	2 "
14 '					
	THIRD OUTER	3" - 24"	2 - 6	⅛" - ½"	¾"

Laths of riebeckite are generally disseminated through the bands which consist predominantly of minnesotaite, but in the wider minnesotaite bands riebeckite may be more concentrated in thin bands which do not have the characteristic sharp contacts that generally separate the bands of massive riebeckite from the adjacent bands. The layers of massive riebeckite generally contain little magnetite. The best known of these layers of massive riebeckite attains a thickness of six feet in the Westerberg Valley, and lies between the Outer Reef and the Second Outer Reef. It is known as the "Blue Bank", or more specifically as the "Outer Reef Blue Bank". It does not weather readily and generally retains its blue colour right up to the surface making it a useful underground and surface-marker. It is a tough rock to drill and to blast and is avoided as far as possible in underground development-work. Another invaluable underground marker is the so called "Bottom Main Reef Marker", which is a dark brown to black, cryptocrystalline band, one inch thick, without any lamination and a characteristic conchoidal fracture. This marker has been found wherever this portion of the Westerberg Asbestos Horizon has been exposed in the Koegas-Westerberg area.

iii. The Mudstone Zone. Lying between the Westerberg Beds and the Tillite Zone is the Mudstone Zone; a succession of relatively soft, non-magnetic strata which generally occupies the valleys between the ranges of hills formed by the resistant Banded Ironstone Beds. About 900 feet above the base of the Mudstone Zone is a layer of chert which is approximately 20 feet thick. The thickness of the Mudstone Zone is conservatively estimated at 2,500 feet. It can be subdivided readily as detailed below.

Immediately above the Westerberg Beds lie the Lower Shale Beds, a succession of 500 feet of shale of which good exposures are seldom seen on surface. When unaltered, they are composed of finely-banded grey, green, and blue, argillaceous material with occasional bands of massive, blue riebeckite up to six inches thick. However, on weathering they acquire a very thin, black coating. The fine banding visible in unaltered specimens obtained from bore-holes is less clear in the surface-exposures, where individual layers appear thicker, with dark blue, brown and greenish brown colours predominating.
Bands of chert and magnetite, typical of the Banded Ironstone Zone, are completely absent in the Mudstone Zone, in which only some layers contain a small amount of finely disseminated, small crystals of magnetite.

Following on the Lower Shale Beds is a succession of mudstone, known as the Lower Mudstone Beds. These rocks are some 400 feet thick, and are green when unaltered but yellowish green to brown near the surface. The rock is extremely fine-grained and compact; banding is practically absent and it is frequently impossible to determine the dip of the rock even in a fresh piece of drill-core. The transition between the Lower Shale Beds and the Lower Mudstone Beds is gradational. [Plate I (a) 1].

Microscopic examination of unaltered samples of the rock immediately above the Westerberg Beds showed that the bands of massive riebeckite are identical with those found in the Banded Ironstone Zone.

The banding of the fresh, finely laminated shale is generally uniform with occasional swellings and pinchings. The shale contains some soft, pale grey bands that show distinct, although not violent, reaction with dilute hydrochloric acid, especially when the rock is powdered. Microscopic examination showed that they consist of extremely fine-grained, microcrystalline carbonate. The greater part of these bands is semi-opaque, but some present a "blotchy" appearance owing to local concentration of more translucent crystals of carbonate into "blobs" with average diameters of up to 0.25 mm. In some bands of carbonate the position is reversed and semi-opaque "blobs" lie in a clearer, microcrystalline matrix of carbonate.

Brownish yellow bands are frequently found. They are similar in composition to the brownish yellow bands occurring at Buisvlei which have been described on page 44, but no large rhombs of carbonate, characteristic of the rock on Buisvlei, are present. These bands consist of an intimate mixture of microcrystalline quartz and minnesotaite with varying amounts of riebeckite and a little carbonate. A typical example is illustrated in Plate V (c), and the X-ray diffraction pattern of this rock is given in Table II, page 23. Riebeckite is present in the rock as small laths with irregular outlines, and they are up to 0.01 mm. long and 0.005 mm. wide. Occasionally these laths are clustered together in bundles orientated at random, which cause the bands in which they are present to have a speckled appearance. The riebeckite may also lie in thin bands parallel to the bedding planes of the rock, but without very definite boundaries. These thin blue bands contribute to the very finely banded appearance of the rock in hand-specimen.

Chloritic material, absent in the Banded Ironstone Zone, makes its appearance in the Lower Shale Beds not far above the Westerberg Beds. The mineral is present in well-defined bands varying in thickness from 0.01 to 0.1 mm., although under high magnification bands of slightly different shades and of the order of 0.002 mm. thick may be visible. The chloritic material in these bands is cryptocrystalline to microcrystalline and crystals large enough to exhibit the typical anomalous blue interference colour are seldom visible. A feature of the bands of chloritic material, which makes them comparatively easy to distinguish under the microscope from typical bands of minnesotaite, is their preferred orientation parallel to the bedding.

Small, perfect rhombs of carbonate, up to 0.06 mm. long, are disseminated through the rock in places or occupy a specific layer in the rock, generally with their major axes parallel to the bedding planes [Plate IX (a)]. These rhombs are always translucent and no trace of relict bedding, which would indicate a replacement origin for these rhombs, was found in any of them. Where bedding planes do appear to persist through a rhomb, for example through the large rhomb shown on the left-hand side of Plate IX (a), closer examination under the microscope revealed that these rhombs are either underlain or overlain by the darker horizontal bands in the section: the thickness of a normal section being twice the length of the major axes of the rhombs.

As one proceeds upwards in the succession, the banding becomes less clear, until eventually the rock is no longer a shale but a fine-grained, compact, green mudstone. Microscopic examination of samples of typical unaltered mudstone obtained from drill-cores showed that the rock consists of extremely fine-grained carbonate, quartz and chloritic material with occasional larger crystals of carbonate. None of the minerals shows any preferred orientation. Some layers also contain a few small grains of magnetite.

The X-ray diffraction pattern for a sample of this rock is given in Table VI.

TABLE VI.

X-RAY DIFFRACTION-PATTERN OF MUDSTONE.

(Co radiation. Only the strongest lines given.)

MUDSTONE Westerberg		QUARTZ A.S.T.M. Card 5-0490		SIDERITE A.S.T.M. Card 3-0746	
dA	Int.	dA	Int.	dA	Int.
12.1	25				
9.9	5				
4.26	35	4.26	35		
3.58	5			3.61	27
3.34	100	3.34	100		
2.79	20			2.80	100
2.73	10				
2.58	5				
2.45	15	2.46	12		
2.35	5			2.36	17
2.28	10	2.28	12		
2.23	5	2.24	6		
2.13	15	2.13	9	2.13	20
1.98	5	1.98	6		
1.96	3			1.96	20
1.82	20	1.82	17		

(X-ray diffraction-pattern measured in the Government Metallurgical Laboratory, Johannesburg, and at the Ceramics Unit of the Council for Scientific and Industrial Research, Pretoria.)

After the lines belonging to quartz and carbonate have been eliminated, the only lines unaccounted for are the relatively weak lines at 12.1, 9.9, 2.73 and 2.58A, which do not correspond with those of pure chlorite. The X-ray diffraction pattern showed no change after the sample had been treated with glycol, or heated to 600°C for one hour. However, after heating a sample to 700°C for two hours, the lines at 12.1A and 9.9A disappeared. (The fate of the lines at

2.73A and 2.58A was not investigated). It is concluded that the green micaceous material is not a pure chlorite, but a mineral with a mixed-layer structure. Possibly more than one type of micaceous mineral is present.

No bore-holes have been drilled in which the topmost portion of the Lower Mudstone Beds, the Chert Layer, the Upper Shale Beds or the Upper Mudstone Beds have been intersected in the Fresh Zone. The description of these rocks given below is therefore that of their weathered equivalents.

As samples are taken progressively higher in the mudstone, small, angular fragments of clastic quartz and clastic feldspar (in which polysynthetic twinning is clearly visible) make their appearance. They lie in a matrix of altered chloritic material and cryptocrystalline quartz with occasional small grains of carbonate. [Plate IX (b)]. The outlines of the particles of clastic quartz are sometimes slightly embayed and the quartz is replaced by chloritic material.

The mudstone, as exposed on surface, is green on a freshly broken surface, but the rock weathers to chocolate-brown, round boulders. It is extremely fine-grained, tough, and breaks with a subconchoidal fracture. The clastic particles are too small to recognise with the unaided eye, and the rock may easily be mistaken both in outcrop and in hand-specimen for a fine-grained mafic igneous rock.

Above the mudstone is a chert layer, approximately 20 feet thick. This layer is composed of bands of off-white, grey, greenish and brown chert. One of the bands of brown chert contains subangular and rounded fragments of paler chert, and resembles somewhat an intraformational conglomerate or breccia. The lowermost band of chert often has a characteristic pitted appearance. The chert is more resistant to weathering than the adjacent strata, and outcrops are fairly easy to follow in the field, thereby making this layer a valuable marker in the generally soft rocks of the Mudstone Zone.

The Upper Asbestos Horizon is sporadically developed in the chert layer and has been exposed in both the Koegas and the Weilbach Valleys, but is not being mined in the area. The workings near the western boundary of the adjacent farm Kwakwas 0.318 are also on this horizon, but they are uneconomical and were abandoned in 1933.

Following on the chert layer is a succession of shale, over 300 feet thick, that weathers blue-black and is indistinguishable in the field from that found at the base of the Mudstone Zone. The shale again gradually makes way for a succession of more than 1300 feet of mudstone which, like that below the chert layer, contains progressively more clastic particles as one moves upward in the succession. In the uppermost 200 feet of the mudstone are layers of more ferruginous material, up to 20 feet thick, which are more resistant to weathering and in some parts of the area form a series of low, parallel ridges, separated by the usual green mudstone. Occasional thin bands of red and pale grey chert are developed in the ferruginous layers, and bedding planes are more easily recognised.

iv. <u>The Tillite Zone</u>. The exposure of the Tillite Zone nearest to Koegas is on the adjacent farm Koegas Puts. Its total thickness is less than 50 feet. The tillite layer itself if approximately 10 feet thick, and is separated from the Ongeluk lava by a layer of mudstone of approximately the same thickness. The tillite is seldom well exposed on surface as it decomposes rapidly on weathering. On Koegas Puts the matrix of the rock is reddish brown to grey-green, and it encloses small, angular fragments of chert and jasper. The inclusions seldom exceed one inch in length and striated pebbles are rarely seen. The tillite layer is separated from the topmost shaly mudstone of the Mudstone Zone by 20 to 30 feet of greenish brown mudstone in which lenticular bands of carbonate are developed. These bands attain a maximum thickness of 10 feet, but pinch out rapidly when followed along the strike. Near the southern tip of the Abramsdam Syncline the layers of carbonate are well developed, attain thicknesses of up to 25 feet, and often form low ridges of brown rock with typical weathered surfaces which resemble the skin of an elephant.

Microscopic examination of a sample of the carbonate-rock from Koegas Puts showed that it consists of euhedral to subhedral crystals of magnetite, up to 0.2 mm. across, disseminated in a fine, even-grained matrix composed of well-interlocking crystals of carbonate which have polygonal outlines and an average diameter of 0.01 to 0.02 mm. The refractive indices are nO = 1.739 and nE = 1.544, which correspond to those of ankerite. Veins in the rock are filled with secondary carbonate and quartz.

The Tillite Zone is overlain by lava of the Middle Griquatown or Ongeluk Stage. At the base of this Stage on Koegas Puts the lava is amygdaloidal, the cavities being usually filled with quartz and carbonate.

C. THE SUPERFICIAL DEPOSITS.

Along the slopes of the hills the rock formations are generally covered by talus. Outcrops of the less resistant, thick sill in the Banded Ironstone Zone are frequently obscured by large slabs and small pieces of hard, resistant banded ironstone and jasper from the crests of the hills. Gravel composed of fragments of banded ironstone and slate covers most of the rock formations in the valleys. Deposits of pure sand are only found in the immediate vicinity of the Orange River, and in occasional sand dunes, e.g. the one which crosses the boundary between Koegas and Hakschin near the Orange River. These sand dunes become abundant from about 15 miles north of Koegas, until eventually thousands of square miles of the area between Koegas and the border of the Bechuanaland Protectorate are covered by recent (Kalahari) sand.

Northwest of the Westerberg Valley the Orange River makes a sharp bend from northwest to southwest. A thick deposit of alluvial sand between the Westerberg Valley and the present course of the River marks the progressive outward-cutting trend of the River by erosion of the strata on the nip and deposition of sand on the fill.

Few outcrops of surface-limestone are to be seen in the area, but a layer immediately below a thin cover of gravel is more widespread than is generally supposed. This capping of limestone has been encountered in nearly every prospecting-pit or - trench made, and repeated examination of holes dug for poles carrying power or telephone-lines, sited without any regard to the geology, has confirmed the universal nature of the surface-limestone.

The limestone is slightly off-white and so hard that explosives often have to be used to remove it from asbestos-bearing strata. Unsorted, angular to subangular fragments of oxidized banded ironstone, orientated at random and sometimes containing blue or oxidized asbestos, are cemented together above the suboutcrop. The surface-limestone may also replace highly weathered underlying rocks, and it is interesting to note that bands of crocidolite are replaced last of all, although they may be folded to a remarkable degree during the replacement of the enclosing strata. Limestone is also deposited in cracks and fissures up to a depth of 30 feet, and sometimes more, below surface.

There is a gradual decrease in the amount of surface-limestone as one proceeds northwards from Koegas, until, in the Kuruman area, there is no capping of surface-limestone over the banded ironstone beds.

Various explanations regarding the origin of the limestone have been put forward in the past, the main difficulty being the supposed absence in the Lower Griquatown Stage of the minerals from which the limestone could be formed. The samples of banded ironstone studied by Peacock (1928, p. 267) showed "no vestige of earlier siderite" and he felt that the inference that the rhomboidal areas described by Rogers (1907, pp. 32 - 33) are replaced siderite, was "not beyond question". Pascoe (1941, pp. 417 - 418) postulated that the limestone had been formed as a result of marine inundation of the asbestos-bearing beds south of Griquatown, and that the superficial deposits of limestone originated from erosion of the Dolomite of the Kaap Plateau. Four years later Du Toit (1945, pp. 163 - 165), studying specimens from less weathered strata than Peacock, described an increase in the carbonate content of the ironstone with depth below surface, but did not comment on the surface-limestone. In view of the high carbonate content of the fresh rocks of the Lower

Griquatown Stage described earlier, the writer feels that the origin of the surface-limestone can be explained satisfactorily by the normal process whereby the carbonate-minerals present in the unweathered rocks are dissolved by meteoric water and redeposited at or very near the surface by evaporation. This process is still functioning today.

The absence of a capping of surface-limestone in the Kuruman area is explained by the difference in climate. There the annual rainfall exceeds 15 inches, whereas at Koegas it is approximately half that amount. Kuruman is also situated approximately 2000 feet higher than Koegas, and has a cooler climate. Consequently, the ratio of evaporation to rainfall is much lower in the Kuruman area, and effectively prevents the extensive formation of surface-limestone.

D. THE IGNEOUS INTRUSIONS.

Intrusive sills and dykes are abundant in the Koegas-Prieska area, and belong to at least two distinct ages of intrusion which may be subdivided as follows:

1. Diabasic Rocks related to the Ongeluk Volcanics.

These intrusions are in the form of sills or thin sheets injected more or less along the planes of stratification of the older sediments. They are found in any position in the succession, but their outcrops are often obscured by a covering of surface-limestone or talus of banded ironstone or gravel. Numerous sills of varying thickness and lateral extent have been located, and the more important ones have been discussed in the section dealing with the sedimentary rocks of the Lower Griquatown Stage.

These sills are considered to be a related and slightly younger intrusive phase of the Ongeluk volcanics.

2. Dykes:

All dykes found in the area under discussion cut nearly vertically through the Lower Griquatown Beds, and are therefore later than the latest folding, which is of Post-Waterberg age. It was not possible to determine the exact age of the dykes in the Koegas area, but Truter et al (1938, pp. 46 - 49) and Visser (1944, p. 216) described dykes of two ages in the Postmasburg area, which they dated as (a) Post-Waterberg, Pre-Karroo and (b) Karroo dykes. Visser (idem) states that the Karroo dykes are magnetic, whereas the Pre-Karroo dykes are non-magnetic.

Outcrops of dykes are seldom seen, but their presence can readily be deduced from depressions on the surface, caused by the relative ease with which they weather. [Plate IV (b)]. The dykes have been responsible for most of the "poorts" and numerous conspicuous necks and deep cuttings through the banded ironstone hills.

Numerous dykes have been exposed in underground workings in the Koegas-Prieska area, and they confirm that these depressions do, in fact, coincide with the outcrop of the dykes. In the Westerberg Valley the dykes vary in width from less than one foot to over 300 feet. Some of the larger dykes can be followed on surface for many miles. Their dip is generally very steep towards the southwest or becomes nearly vertical.

With few exceptions, all major displacements of the sedimentary rocks are found to have taken place along planes now occupied by the dykes. They have intruded along pre-existing faults and planes of fracturing. The most favoured direction along which dykes are found is north-northwest to south-southeast, with occasional dykes at right angles to this direction.

The metamorphic effects caused in the sedimentary rocks adjacent to the igneous intrusions is discussed in Chapter III.

E. GEOLOGICAL STRUCTURE.

1. General.

The geological structure of the greater portion of the asbestos fields in the Cape Province, from 20 miles northeast of Koegas to five miles south of Kuruman, has been described in detail recently by Visser (1944), Boardman and Visser (1958) and Truter et al (1938). The rocks of the Lower Griquatown Stage are exposed as a series of interconnected, shallow, doubly-plunging synclines. (Plate XI.)

Apart from subordinate contemporaneous folding described in Chapter III, the rocks of the Lower Griquatown Stage were subjected to two periods of folding. The first period of folding was relatively gentle, and took place prior to the deposition of the Gamagara and Matsap Formations, according to Visser (1944, pp. 247 and 252). After the deposition of these Formations, their constituent rocks as well as those of the underlying Transvaal System were subjected to more intense pressure directed from the west, as a result of which they were intensely folded in certain regions. In the area of maximum pressure, near Postmasburg, numerous low-angle thrust-faults were developed (Visser, 1944), and in the Koegas-Prieska area thrust-faulting probably took place along the Doornberg Fault.

The Doornberg Fault strikes approximately northwest, and passes about eight miles southwest of Prieska, West of this fault the Lower Griquatown Stage has been eliminated, and the writer confined his work in the Koegas-Prieska area to the ground east of the fault. The nature of the Doornberg Fault was not studied in detail, as there appears to be no relationship between this fault and the development of economic deposits of amphibole asbestos. Members of the

Geological Survey of the Union of South Africa are currently making a study of the tectonics of the Doornberg region and the nature of the fault.

At distances greater than ten miles from the Doornberg Fault, the geological structure is comparatively simple: large, open folds are the rule and large faults are absent. However, as the Doornberg Fault is approached, folding becomes progressively more intense and many normal and thrust-faults of varying magnitude are present. The Koegas-Westerberg mining-area lies immediately to the east of the Doornberg Fault.

2. The Koegas-Westerberg Area.

The strike of the Doornberg Fault swings from northwest to slightly west of north on the farms Asbestos Hills and Schalksdrift. (Plate XII). At the Koegas-Westerberg Mine, crocidolite is extracted from the Westerberg Asbestos Horizon on the farms Asbestos Hills, Hounslow and Koegas. The distance from the Doornberg Fault to the farthest boundary of these farms is less than six miles, and to the nearest workings in the Westerberg Syncline the distance is approximately half a mile. Consequently, all the workings lie within the intensely folded belt adjacent to the Doornberg Fault.

The conspicuous preferential alignment of the principal dykes approximately parallel to the Doornberg Fault is clearly shown in Plate XII. Of the larger dykes only two, d1 and d2 (in blocks C2 and C3 on the map), strike approximately at right angles to the Doornberg Fault. The general trend of the dykes suggests that they were emplaced along faults, fractures or joints which were caused by the same stresses that gave rise to the Doornberg Fault. The dykes maintain their general trend regardless of the strike of the folded sedimentary rocks, and may lie parallel to the strike of these rocks, e.g. d3 (D3) and the northern extensions of d4, d5 and d6 (A2); or they may lie at right angles to the strike, e.g. the southern extension of d4 (B3); or oblique thereto, e.g. in the Westerberg Syncline (D2). It follows, therefore, that the main faulting took place subsequent to the folding in the Koegas-Westerberg area.

The general structural pattern in the Koegas-Westerberg area north of the Orange River is that of three synclines, all pitching towards the northeast, and separated by anticlines pitching in the same direction. The synclines are known as the Hounslow Syncline, the Weilbach Syncline, and the Koegas Syncline. The southwestern extension of the Koegas Syncline south of the Orange River is known as the Westerberg Syncline. The axis of the Westerberg Syncline strikes slightly east of north. The anticlines have the same names as those synclines immediately west of them.

A characteristic feature of all the large folds is that their flanks have reasonably regular dips, but small folds are invariably developed on the crests of the anticlines and in the troughs of the synclines (Plate II). The small folds have the same pitch as the large folds. Secondary folds are superimposed on the small folds. Microscopic examination shows folds too minute for the unaided eye to detect.

The general structural pattern of the folds is complicated to some extent by displacement adjacent to numerous longitudinal, transverse and oblique faults of varying magnetude. The following is a brief description of the effects of the folds and the faults on the distribution of the Westerberg Asbestos Horizon in the Koegas-Westerberg mining-area:-

a. The Westerberg Syncline: [Plate IV (a)]

The Westerberg Syncline (D2 and Section GG') is the most regular of the four synclines. The dip of the Westerberg Asbestos Horizon along the western limb of the syncline is about 55 degrees, and along the eastern limb the dip varies between 55 and 75 degrees. These dips decrease steadily with depth below surface. The Westerberg Syncline pitches in a direction slightly east of north at approximately 15 degrees. In bore-hole W4 the Westerberg Asbestos Horizon was intersected between 1066 and 1216 feet below surface. Owing to a small overfold the Inner Reef was intersected three times in this bore-hole. Six parallel, near-vertical dykes, varying in width from 6 feet to 180 feet, cut across the Syncline at an angle of approximately 45 degrees to the strike of the rocks along the flanks of the Syncline.

Bore-holes drilled between the road from Koegas to Draghoender and the Orange River have proved the persistence of economic quantities of asbestos below the thick cover of alluvium, and have also confirmed the extension of the western limb of the Syncline northwards, until it crosses the Orange River and reappears on the surface near the southeastern corner beacon of the farm Hounslow (C3).

b. The Westerberg Anticline:

The eastern limb of the Westerberg Syncline does not cross the Orange River, as the strike of the beds changes abruptly from slightly east of north to south-southeast around the nose of the Westerberg Anticline. At the same time the dip of the strata decreases to approximately 25 degrees to the northeast. Along the eastern flank of the Westerberg Anticline the strike of the Westerberg Asbestos Horizon is roughly parallel to the general trend of the dykes, and it is not cut by any major dyke. The Westerberg Anticline pitches north at approximately the same angle as the Westerberg Syncline.

c. The Koegas Anticline:

The Koegas Anticline is an extension of the Westerberg Anticline. As a result of a series of four step-faults, f1 to f4 (f1 being obscured by alluvium), which strike north-northwest, the Westerberg Asbestos Horizon is again exposed on the surface at three separate localities northeast of the Orange River (C3, C4 and B4).

d. The Koegas Syncline:

The western limb of the Koegas Syncline is an extension of the western limb of the Westerberg Syncline. Along this limb of the Koegas Syncline the Westerberg Asbestos Horizon strikes northeast for a distance of about 4½ miles from the Orange River. For the first 1½ miles from the River, i.e. from MK3* to MK9 (C3 and B3), the dip of the rocks is near-vertical or overturned to as much as 135 degrees. As a result of minor folding, the Westerberg Asbestos Horizon is triplicated at MK5 and MK9 (Section FF'). The folds pitch to the northeast at MK5, and to the southwest at MK9. Exploratory bore-holes and development underground have confirmed that the triplication of reefs at MK5 and MK9 has been caused by the same set of folds which have been exposed on the surface at these two localities as a result of the gentle change in pitch of these folds. The angle of the pitch varies between 0 degrees and 12 degrees. On the eastern side of the transverse fault, f5, which separates MK8 and MK9, the folds are displaced some 300 feet to the south.

Apart from some horizontal displacement alongside fault f9, east of MK9, which will be described in conjunction with the Weilbach Anticline, the Westerberg Asbestos Horizon can be followed without interruption to the northeast of MK9 for a distance of about 2 miles to near the boundary between Koegas and Koegas Puts (B4), where it stops abruptly against a transverse fault, f6, which strikes slightly west of north and alongside which the rocks to the east of the fault have been displaced 1500 feet to the south.

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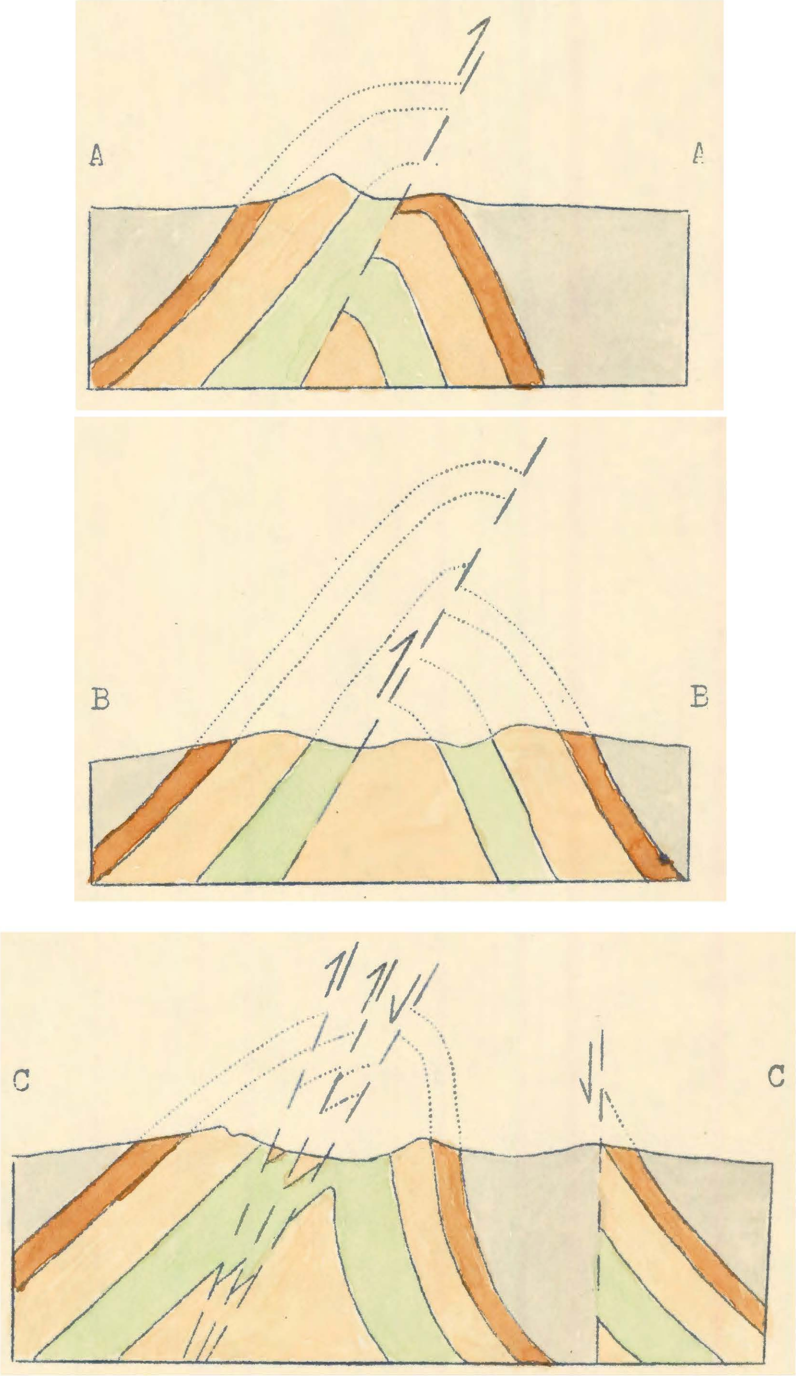
* The prefix "M" before any number indicates reference to a division of the Workings of the Koegas Asbestos Mine, e.g. "MK3" = Division 3 of the workings of the Koegas Division.

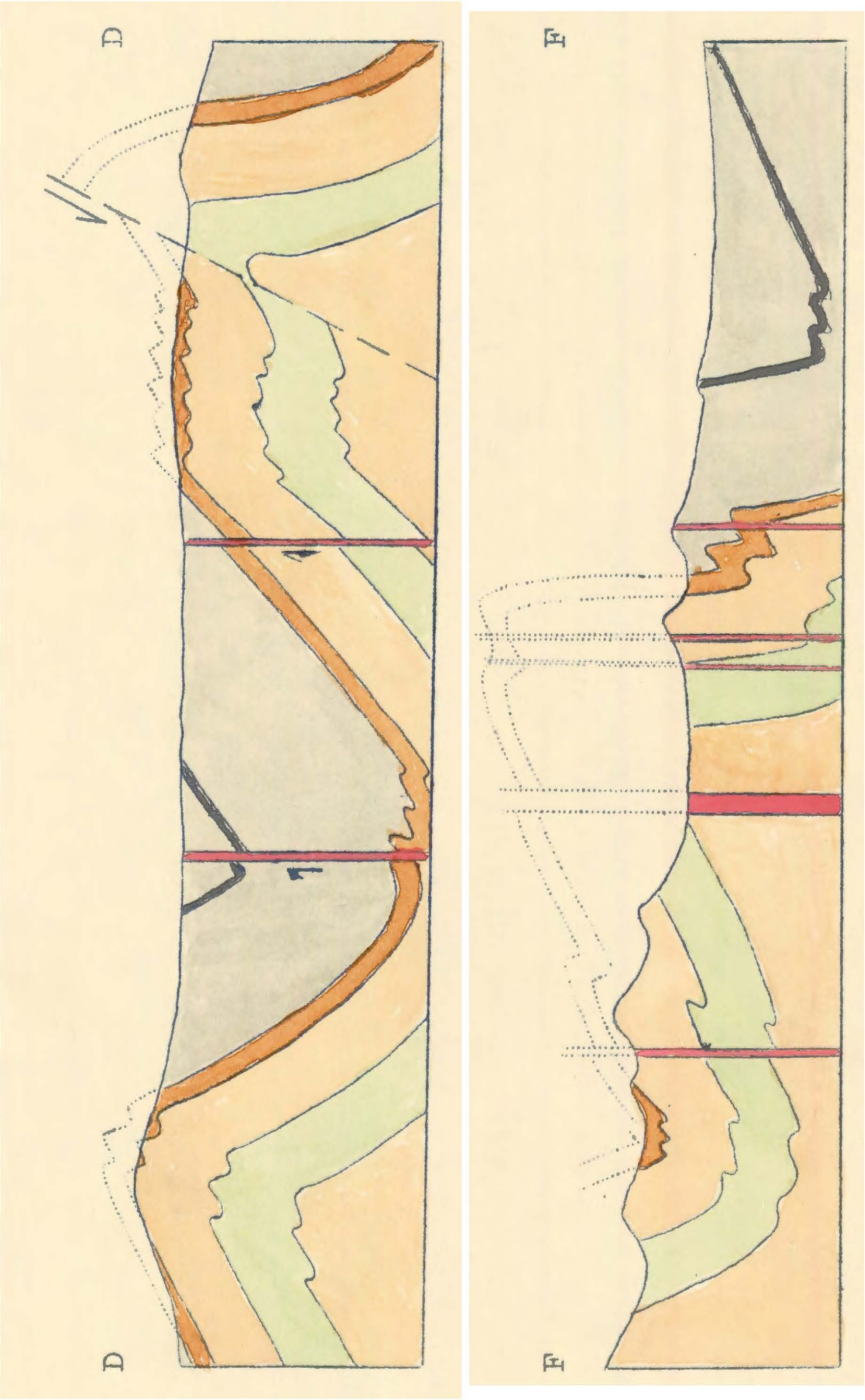
SECTIONS THROUGH THE WEILBACH ANTICLINE

SCALE 1:20,000.



SECTIONS THROUGH THE WEILBACH SYNCLINE AND ANTICLINE.

SCALE 1:20,000.



East of this fault the Westerberg Asbestos Horizon strikes northeast for a distance of 4000 feet (B4) and then starts curving gently around the nose of the Weilbach Anticline, near the boundary between Koegas Puts and Kwakwas (A4). On the nose of the Anticline the Westerberg Asbestos Horizon is displaced some 3500 feet to the northeast by a longitudinal fault, f7.

e. The Weilbach Anticline:

The large, overturned anticline which separates the Weilbach Syncline from the Koegas Syncline is known as the Weilbach Anticline, and is the tightest large fold in the Koegas mining area. A longitudinal thrust-fault, f7, lies approximately parallel to the axial plane of the fold (B3, B4 and A4). (Sections AA' and BB'). This fault is displaced alongside the transverse fault f6. Immediately west of f6, a smaller longitudinal thrust-fault, f8, lies approximately 500 feet north of f7, and a longitudinal gravity-fault, f9, lies approximately 400 feet south of f7. (Section CC'). (Faults f8 and f9 were not found east of f6). The displacement alongside faults f7, f8 and f9 gradually decreases in magnitude westwards, and the three faults slowly converge until west of a point which lies approximately 1 mile to the west of f6 (B3) only the longitudinal gravity fault f9 is present. (Sections DD' and E'E''). This fault causes the slight horizontal displacement of the Westerberg Asbestos Horizon immediately to the east of MK9 mentioned above.

f. The Weilbach Syncline:

The broad structural pattern of the Weilbach Syncline is similar to that of the Westerberg Syncline. The dip of the Westerberg Asbestos Horizon on the western flank of the Weilbach Syncline is of the order of 70 degrees, whereas on the eastern flank the dip is approximately 45 degrees. Subordinate folding causes the repetition of the reefs of the Westerberg Asbestos Horizon in the trough of the Syncline at MK11 (B3), (Plate II), and also along the eastern flank of the Syncline at MK12 (B3), [Plate I (b)]. The Westerberg Asbestos Horizon in the trough of the Syncline is triplicated to the west of MK10 as a result of being thrown down on the western side of the three dykes d4, d5 and d6.

g. The Hounslow Syncline and Anticline:

The structure of these folds is fairly simple, and is shown on Section EE'E''. Apart from some minor folding near the boundary between Hounslow and Pypwater, there are no further large folds on Pypwater north of the Hounslow Syncline. The rocks on this farm strike slightly east of north, and have a general dip of approximately 45 degrees to the east.

III. THE ORIGIN OF THE ROCKS BELONGING TO THE LOWER GRIQUATOWN STAGE.

A. GENERAL:

The problem of the origin of the banded Precambrian iron-bearing formations is a complex one, to which, as yet, no complete solution has been found. Remarkably little has been published regarding the origin of the rocks belonging to the Lower Griquatown Stage, although it is generally accepted that the banded ironstone and the jasper are chemical precipitates. Du Toit (1945, p. 163) suggests that the material was precipitated for the most part as colloidal silicates, though also as double carbonates, in a shallow, probably cold sea, but he does not discuss the source of the material, nor the mechanics of transportation or deposition.

B. THE SOURCE OF THE MATERIAL:

Two strikingly opposed views have been advanced regarding the source of the main constituents, iron and silica, of the Precambrian iron-bearing formations. On the one hand there is the theory that the material constituting these rocks was contributed directly to the ocean by magmas, volcanoes or fumaroles, or by the reaction of sea-water on hot or cold lava. On the other hand there is the theory that the constituents were derived from the continents as a result of weathering and solution, transportation by rivers, and deposition with or without the aid of organisms.

1. Material derived from magmatic Sources.

Van Hise and Leith (1911, pp. 459 - 529) concluded that contemporaneous, iron-rich eruptive rocks were the principal source of iron and silica in the Precambrian iron-bearing rocks of the Lake Superior region. They suggested that the salts were transferred from the igneous rocks to the sedimentary formations partly by decomposition of the constituent minerals and partly by direct contribution by hot solutions which migrated from the eruptive material during its solidification and carried salts from the interior of the magma which had not crystallized, and perhaps in small part by direct reaction of the sea water on the hot lava.

The direct application of the hypothesis of Van Hise and Leith to the origin of the banded ironstone of the Lower Griquatown Stage is not feasible, as this ironstone is not associated with mafic eruptive rocks. Vast regions to the east and the north of the area underlain by the banded ironstone of the Lower Griquatown Stage are covered by lava of the Ventersdorp System, yet the greatest development of banded iron-bearing formations is in the younger Transvaal System. This suggests that the lava was the source of some of the material from which the banded ironstone was formed, not so much during the time of its extrusion, as during its exposure much later. Gruner (1922, pp. 407 - 460) pointed out that a similar relationship also holds between the Keewatin volcanics and the iron-bearing formations of the Lake Superior region, and stressed the absence of extensive bodies of contemporaneous mafic igneous rock in the Biwabik and Gunflint Formations of the Huronian System.

Peacock (1928, pp. 265 - 270) dismissed the hypothesis that the rocks of the Lower Griquatown Stage might represent ancient deep-sea deposits similar to the red clay now slowly accumulating in the deepest part of the ocean, and adoped the view that the greater part of the chlorides now in solution in sea water were emitted from the body of the earth by subaerial and submarine volcanoes. He pointed out that, to be expelled, submarine fumarole vapours must be at a higher prossure than that defined by the overlying column of water, probably at temperatures of several hundred degrees, and, being charged with hydrochloric acid, would cause extensive decomposition of the walls of the fissures traversed. Chlorides of iron, aluminium, lime, magnesium, and of the alkalies would thus be formed with concurrent liberation of silica. The periodic nature characteristic of volcanic and fumarolic action would ensure that these chlorides were transferred to the sea water. For the chlorides to be precipitated, it would be necessary to postulate an alkaline reagent. Peacock suggested either ammoniacal vapours presumably emitted from submarine volcanoes or fumaroles, or soluble alkaline silicates formed in the manner proposed by Van Hise and Leith (1911, pp. 499 - 529), which would then effect the selective precipitation of iron and aluminium as hydrates. The sea water would become neutralized, lime and magnesia would remain in solution to be precipitated later, probably as carbonate and phosphate, and alkaline chlorides would remain in solution. With subsequent uplift of the basin of accumulation this heterogeneous precipitate would become dehydrated and indurated and a rock would be formed corresponding substantially to a ferruginous chert.

There are many objections to Peacock's admittedly speculative hypothesis. It appears unlikely that sufficient material could be emitted from fumaroles within a limited area to form a deposit of banded ironstone as extensive as that of the Lower Griquatown Stage. Gruner (1922, pp. 407 - 460) calculated that 524,000 cubic miles of an aqueous solution containing 1000 parts per million SiO_2 would have been necessary to transport the silica of the Biwabik Formation alone. The magma which could furnish a solution of that volume would probably have to be twenty to forty times as large. To furnish as much iron as is assumed to be in this Formation, it would require 630,000 cubic miles of a solution carrying 100 parts per million of iron (which would require 300 parts per million silica to be in the ratio of silica in the cherts.)

If a fumarolic origin for the Lower Griquatown Stage is postulated, one would expect to find traces of the intense chemical activity associated with the fumaroles, essential to Peacock's theory, preserved in at least some of the formations older than the Pretoria Series. As far as the writer is aware, there is no evidence of any activity of this nature preserved in these formations. It would also be difficult to find in these older formations an adequate source of iron that could be dissolved by fumaroles in sufficient quantities to satisfy the requirements of the Lower Griquatown Stage. There are many serious chemical difficulties to be overcome. Peacock does not state in what form the silica is liberated, or by what process it becomes deposited. Neither does he present an explanation of the ultimate fate of the large quantities of aluminium hydrate that would have been precipitated with the iron, although he previously commented on the low alumina content of the ironstones. It is difficult, if not impossible, to conceive how the heterogeneous precipitate Peacock considered to have been formed, could have assumed a regular banded appearance, with such extreme mineralogical differences between individual bands, through a process of uplift, with dehydration and induration, and later burial beneath younger sediments. Only the main objections to Peacock's hypothesis have been mentioned above, but they appear sufficiently strong to make this theory on the origin of the Lower Griquatown Stage appear most unlikely.

The origin of the rocks of the Lower Griquatown Stage has been dealt with briefly by Wagner (1928, pp. 64 and 65), who stated that there is often a transition-zone between the ironstone and the underlying dolomite. This fact coupled with the absence of recognizable sediment of mechanical origin in the typical banded ironstone indicated to him that the sideritic cherts are marine deposits. He believed them to be chemical precipitates as it had not been proved that iron bacteria are capable of precipitating iron carbonate or silicate. He suggested that the silica may have been in colloidal solution in the sea water and that the iron was directly contributed to the ocean by magmatic waters.

In view of the serious obstacles encountered with hypotheses in which a purely magmatic source of material is postulated, this source is no longer considered seriously, and, with the exception of Goodwin (1956, pp. 565 - 595), the writers of all papers published after 1930 are unanimous in accepting that the material that eventually formed the Precambrian banded ironstone was derived mainly by normal processes of weathering. However, it cannot be denied that notable quantities of both iron and silica may have been contributed to the water of the sea by magmatic sources, and that this material has been incorporated into Precambrian, as well as later iron-bearing formations.

2. Material derived from the Weathering of Continents.

There is no longer any doubt that sufficient material for the formation of the rocks of the Lower Griquatown Stage could have been obtained from the weathering of the rock exposed on the continents at the time this Stage was being deposited. Gruner (1922, p. 455) calculated that the Amazon River could carry sufficient iron and silica to the sea in 176,000 years to form the Biwabic Formation, and furthermore that in a basin the size of that of the Amazon River, a rock of a thickness of only a few feet contains sufficient iron to furnish the quantity required. Such a source would assure a steady supply of material over a long period.

The weathering of the rock exposed on the continent could have been achieved by purely chemical means, or with the aid of organisms. That some form of life did exist at the time the

Pretoria Series was deposted, may be inferred from the algal structures in the Dolomite Series, and Du Toit (1945, p. 143) reported the presence of structures of the Collenia type and traces of other fossils in the banded ironstone in the Kuruman area. The presence of primary pyrite and, in certain areas, graphitic material, also indicates that plant life did exist at the time the Pretoria Series was deposited. Even if terrestial vegetation did not exist, there is no doubt that marine and fresh-water plants did exist, and that they must have been exceptionally abundant to give the little evidence that is now preserved. Consequently, it may be accepted that organic processes were active at the time of deposition of the Lower Griquatown Stage, and that these processes could have made a significant contribution to the solution, transportation and deposition of the material from which the banded ironstone was eventually formed.

Gruner (1922, pp. 421 - 446) and Moore and Maynard (1929, pp. 272 - 303) carried out experiments in the laboratory from which they concluded that compounds of iron and silicon are dissolved during the weathering of rocks. The dissolved material is mainly in colloidal solution and is stabilized by minute quantities of organic matter.

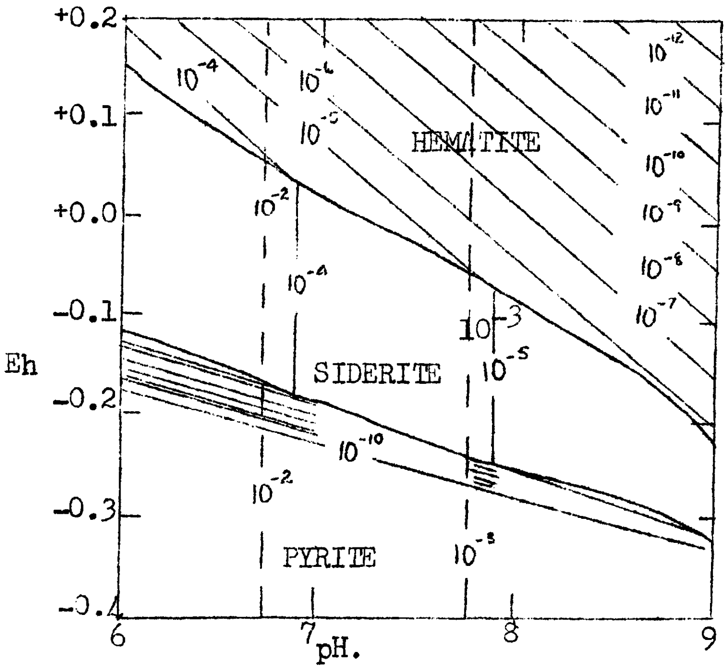
More recent experiments by White, Brannock and Murata (1956) indicate that in water with a pH of between 2 and 9 and at ordinary temperatures, silica in true solution is stable up to a concentration of approximately 110 parts per million. Krauskopf (1956, p. 13) found that the solubility of silica in sea water is not significantly different from that in fresh water.

Iler (1955, pp. 14 and 16) commented on the pronounced decrease in the solubility of amorphous silica effected by traces of aluminium or magnesium ions, presumably as a result of the formation of a protective surface-layer of aluminium or magnesium silicate.

This effect is large enough to alter markedly measurements of apparent solubility carried out in the laboratory.

With the rapid advance of the science of geochemistry during the last decade, came the recognition of the importance of the oxidation-reduction potential (Eh), in addition to pH, relative to the solution, transportation and deposition of iron. Castano and Garrels (1950) showed theoretically that in oxygenated waters sufficient iron can be carried in true solution in rivers to form large iron-bearing deposits. They confirmed these theoretical predictions in the laboratory, with experiments in which the Eh and pH of the solutions were carefully controlled.

Krumbein and Garrels (1952, p. 15) plotted the activity of ferric plus ferrous iron in mols per litre in the form of contour-lines on an Eh-pH diagram. (Fig. 1). From this diagram it may be seen that there is a restricted range in which significant concentrations of iron can be carried. It lies almost entirely within the siderite field, and especially within that part of the siderite field lying at pH values of 7 or less. Any solutions with characteristics lying outside this range of composition cannot carry more than 10^{-4} mols per litre of iron. Presumably, then, iron must be transported in true solution in media with approximately these characteristics, whereas effective transport of calcium measured in the same way (with 10^{-4} mols per litre as a cut-off point) can take place anywhere on the diagram. It should be pointed out explicitly that this treatment does not include iron carried in suspension.



<u>FIGURE 1.</u>

Stability diagram of hematite, siderite and pyrite, showing activity of ferrous and ferric ion (solid contours) and activity of calcium ion (dashed lines) expressed in mols per litre. (After Krumbein and Garrels).

Mason (1958, pp. 145 - 148) states that recent investigations have shown that on weathering a silicate mineral goes into ionic solution during the initial attack, and even silica and alumina are in true ionic solution, at least for a short time, but the ions tend to aggregate and form clusters of colloidal size. According to Rankama and Sahama (1950, p. 554) mica-like clay-minerals may be formed from silica and alumina, and feldspar, mica and zeolites of sedimentary origin are known. When first formed colloidal aggregates are probably amorphous, but, on ageing, orientation into definite crystal lattices takes place (Mason, 1958, pp. 145 - 146). It follows that these colloidal aggregates must be considered as minerals (Rankama and Sahama, 1950, p. 202).

From the experiments quoted above, the writer concludes that silica and compounds of iron were carried to the basin of deposition of the Lower Griquatown Stage both in true ionic solution and in colloidal solution. Some of the silica in solution may also have reacted with other substances before reaching the basin of deposition to form complex silicates with chemical compositions similar to those of some of the silicate minerals now present in the banded ironstone of the Lower Griquatown Stage.

C. THE MODE OF DEPOSITION OF THE ROCKS OF THE LOWER GRIQUATOWN STAGE.

The marked change in facies of the rocks of the Pretoria Series in the Transvaal and in the Cape Province indicates that immediately before the deposition of the Pretoria Series the sea retreated towards the west because the surface of the land had been gently raised. The material from which the Lower Griquatown Stage was formed must have been transported over an area of low relief so that the load of clastic material in the rivers could be separated from the material in solution which was supplied to the Northern Cape geosyncline. It will be shown later (page 95) that this geosyncline was probably a long, shallow basin separated from the open sea by a low, off-shore buckle.

The approximate outer limit of the geosynclinal basin now exposed is indicated in Plate XI. The western boundary is mostly covered by Kalahari sand, and has also been appreciably displaced by faulting. The present distribution of the rocks of the Lower Griquatown Stage is shown clearly by inliers of the Ongeluk or Middle Griquatown Stage, which are preserved in elongated, shallow, doubly-plunging synclines, separated by equally gentle arches in which the lowermost strata of the Lower Griquatown Stage, or even the uppermost strata of the Dolomite Series, are exposed.

In the portion of the Abramsdam Syncline mapped by the writer it was found that the stratigraphical succession of the rocks of the Lower Griquatown Stage was remarkably consistent. The succession of the rocks of portions of the Dimoten and Ongeluk-Witwater Synclines described by Truter et al (1938, pp. 18 - 20) and Boardman and Visser (1958, pp. 13 - 19) respectively is also very consistent, but differs from that of the Abramsdam Syncline described in this thesis in Chapter II. Whether the change in facies of the rocks of the Ongeluk - Witwater Syncline and the Abramsdam

Syncline is abrupt or gradational could possibly be determined by detailed mapping of the area between that covered by Sheet 175 of the Geological Survey of the Union of South Africa, and the Koegas-Prieska area. This area was not included in the present investigation.

A possible explanation for the change in facies may be that the smaller basins already existed in the main geosyncline at the time of deposition of the Lower Griquatown Stage, but that they were accentuated as a result of folding during Pre-Loskop and Post-Matsap time. Material was transported to all of these basins under the same areal conditions, but, owing to differences in the size and location of the smaller basins, probably combined with local differences in the type and quantity of material supplied to each basin, a succession of rock was formed in each basin that differs in detail from that in the other basins but appears similar when seen as a whole.

In the description that follows the details refer to the Abramsdam Syncline, of which the Koegas-Prieska area forms a part, but the general principles may be applied to the whole of the geosynclinal basin in the northwestern Cape Province.

As the water of the rivers entered the basin of deposition, it mingled with the sea water with the result that the material in solution was no longer in equilibrium with its environment. Some of the material in solution in the river water may have reacted with substances present in the sea water. Thus colloidal silicates entering the sea and which possibly contained only a small amount of the elements magnesium, sodium and potassium, may now have acquired them from the sea water, and they would have been precipitated with the material brought into the sea in solution. According to Rankama and Sahama (1950, p. 675) the minerals formed by halmyrolysis include, among others, glauconite, greenalite and chamosite. These minerals are considered to be formed only in a marine environment.

The material in solution may have been precipitated as a result of either inorganic processes or biochemical processes. Microscopic examination of unweathered specimens of banded ironstone from the Lower Griquatown Stage revealed no remains of structures which the writer could interpret as the remains of living organisms, but Gruner (1922, pp. 421 - 446) described thin sections made from specimens obtained from the iron-bearing formations of the Lake Superior region, which showed minute structures which were identified as iron bacteria, bacilli and algae, from which he concluded that the precipitation of silica, iron and part of the organic colloids was chiefly caused by algae and bacteria, although it was also possible that inorganic reactions caused much colloidal silica, iron and organic matter to be precipitated.

Moore and Maynard (1929) carried out various experiments to determine the effect of various salts as precipitants of a mixture of silica and ferric oxide hydrosols, stabilized by organic matter, in concentrations as could be expected in natural river water coming in contact with the electrolytes of the sea. It was found that ferric hydroxide was precipitated in a few days, whereas silica was not completely coagulated after several months. From the experiments carried out it was shown that the lower the concentration of a silica hydrosol, the greater the time required for its coagulation by electrolytes. This suggests that the silica particles gradually gravitate towards the bottom and, when a definite concentration has been reached, the electrolytes are able to bring about coagulation.

Discussing the origin of the banded ironstone of the Dolomite Series in the Thabazimbi area, Du Preez (1944, pp. 263 - 360) thought that the ironstone had not originally been sideritic.

He considered the results of Moore and Maynard's experiments and came to the conclusion that the material was derived from the weathering of adjacent higher ground, was transported to the sea by rivers, and that chemical precipitation of this material had given rise to the banded ironstone formation.

Krauskopf (1956, pp. 1 - 26) subsequently found in the laboratory that dissolved silica in dilute solution is not coagulated by sea water, but remains stable indefinitely in concentrations up to the equilibrium values determined by dissolving amorphous silica directly. He concluded that the origin of chert in marine sediments cannot be accounted for by inorganic precipitation, except locally near volcanic centres, and that the precipitation of silica from sea water must, therefore, be effected by organisms. He quotes the experiments described by Jorgensen (1953), which demonstrated impressively the capacity of diatoms for removing silica from solution.

Bien et al (1958, pp. 35 - 54) demonstrated that silica is also precipitated inorganically, and that both suspended matter from the river water and electrolytes in the sea water are necessary for maximum inorganic precipitation.

Because of its occurrence in a wide variety of sediments, chert appears to be largely independant of the Eh and pH of the environment in which it is precipitated. Iron-bearing silicates are also present in all the rocks of the Lower Griquatown Stage.

There can be little doubt that the silica and some of the silicates were precipitated in a colloidal condition. In the description of the Banded Ironstone Zone at the Buisvlei Mine given on p. 45 , mention was made of spherical "blobs" of fine-grained, matted crystals of riebeckite, surrounded by a thin mantle of yellowish brown rock which consists of a mixture of carbonate, quartz and minnesotaite. These "blobs" lie in a layer of yellowish brown rock with the same composition as that of the mantle around the riebeckite "blob". The layer of yellowish brown rock lies between two bands of magnetite, which have been pushed around the "blob" of riebeckite and its yellowish brown mantle [Plate IV (c)]. Bands of riebeckite, identical with that in the "blob", are interbedded with the bands of magnetite and yellowish brown rock both above and below the "blob". The only explanation for presence of these "blobs" in essentially unmetamorphosed sediments of this type is that, during deposition, some the material that normally would have formed a band of riebeckite upon settling to the bottom, had become suspended as a large colloidal globule in the water, and had settled down to the bottom after the lower magnetite band had been precipitated, and during the time that the yellowish brown band was being precipitated. Some of the material that was being precipitated to form the yellowish brown band was also precipitated around the globule of colloidal material as it sank to the floor of the basin of deposition. As this globule settled on the magnetite band, it is possible that it sank slightly into it, and that a little magnetite was pushed up along the side of the globule. After the yellowish brown band was precipitated, a new layer of magnetite was formed on top of it and over the riebeckite globule, which was still protruding slightly above the depositional surface. This caused a slight bulging of the upper magnetite band. During deposition of the next thicker, yellowish brown band, this bulge was gradually reduced, so that the higher magnetite bands show no sign of disturbance. Compaction of the sediments under their own weight would gradually press the riebeckite "blob" deeper into the bands above and below it, the "blob" making room for itself by pushing material from its top and bottom to the side.

It is possible that some of the ferruginous material that entered the basin of deposition of the Lower Griquatown Stage in solution may have been precipitated by organisms, but it would be difficult to explain how iron could be deposited by biochemical processes in the form of iron oxide, iron carbonate or iron sulphide in alternating layers as described on page 44. Consequently, one is led to the conclusion that the deposition of these minerals in the Lower Griquatown Stage was governed by purely chemical processes. This conclusion is supported by the work of Krumbein and Garrels (1952), who found that the field of stability of each one of these minerals may be delimited on an Eh-pH diagram. (Fig. 1.) They stated that the boundaries between the fields of stability between pyrite, hematite, and siderite as delimited on this diagram are essentially independent of temperature, pressure and composition of the sea water from which they are precipitated. The quantity of a particular mineral that is precipitated depends on the quantity of the constituents available, but a change in deposition from one mineral to another will not take place unless there is a change of Eh or pH of the environment.

Huber and Garrels (1953) conducted a series of experiments to test the validity of the theoretical relations on which the conclusions of Krumbein and Garrels were based. The theoretical fields as calculated by Krumbein and Garrels and the stability fields as determined from the experimental data by Huber and Garrels show remarkable agreement. Furthermore, the boundaries between the fields of stability are not changed markedly by the differences between the experimental system and sea water.

Examination of unaltered specimens of banded ironstone of the Lower Griquatown Stage, under the microscope and by means of X-rays, showed that iron is present in these rocks in the form of a silicate, a carbonate (with varying quantities of calcium and magnesium, as shown in Table I), and as magnetite. Hematite, martite, limonite and goethite are present only in weathered banded ironstone. Peacock (1928, p. 248) found that amorphous, hydrated ferric oxide was the most abundant iron compound in the banded ironstone. His conclusion that ferric oxide is the earliest iron compound and that magnetite must have formed by the partial reduction and crystallization of earlier ferric oxide, was based on examination of specimens that had been highly weathered, and, in the light of our present knowledge, therefore incorrect. Although completely unweathered specimens of banded ironstone had not been exposed at the time the observation was made, Du Toit (1945, p. 176) already found that, excluding pyrite, the ore in the freshest material is essentially magnetite. He concluded that any other oxides of iron in the more or less weathered varieties of banded ironstone must therefore be secondary. Vermaas (1952, p. 214) mentions hematite and goethite associated with amosite, and states (p. 228) that some of the magnetite bands associated with amphibole asbestos are composed of a mixture of magnetite and hematite. Vermaas does not specify the exact locality from which his specimens were obtained, and the writer suspects that the specimens examined by him, and which contained hematite and goethite, were obtained from the Weathered Zone, and the presence of these minerals is therefore of no particular significance in an investigation concerned with the origin of banded ironstone. In the Thabazimbi area, Du Preez (1944, p. 331) found that "there is not the slightest doubt that magnetite is the oldest ore mineral in the banded ironstones".

It is usually accepted that magnetite is formed at a high temperature, especially when present in rocks of magmatic origin, and that its presence in a rock of sedimentary origin is indicative that the rock had been subjected to a moderate to high degree of metamorphism. Du Preez (1944, p. 331) considered the development of magnetite in the banded ironstone of the Dolomite Series in the Thabazimbi area to be the result of thermal metamorphism exercised by the Bushveld Complex. Du Toit (1945, p. 193) concluded that the magnetite "screens" lying adjacent to bands of amphibole asbestos represented excess material pushed out ahead of growing crystals of amphibole asbestos. Du Toit considered the amphibole asbestos to have formed as a result of dynamic metamorphism of the banded ironstone, so that this magnetite must obviously also be considered a metamorphic mineral. Peacock (1928, p. 248) concluded that the magnetite had been formed by partial reduction of earlier ferric oxide. Vermaas (1952, p. 228) stated that the grade of metamorphism to which the banded ironstone had been subjected, is indicated by the state of the iron oxide, as metamorphism of iron oxide is a process of reduction from goethite through hematite to magnetite. In view of the presence of hematite in some of the bands of magnetite in the specimens examined by him, he concluded that the banded ironstone had been subjected to a moderate degree of thermal metamorphism.

However, Peacock (1928, p. 274) already pointed to the complete absence of evidence in favour of severe thermal or contact-metamorphism in the banded ironstone of the Cape Province, and suggested that this rock had been subjected to only a very moderate rise of temperature, such as would be produced by simple burial to moderate depths. Hall (1930, p. 256) supported the views put forward by Peacock. It will be shown later in this thesis (pp. 105 and 110) that the temperature of the banded ironstone of the Lower Griquatown Stage never exceeded 250°C. Because hematite changes to magnetite only above 1452 ± 5°C at 1 atmosphere pressure of oxygen and above 1388 ± 3° at 0.2 atmosphere pressure of oxygen, and siderite is stable to 500°C at least (Ontario Research Foundation, 1958, pp. 3 and 15), it follows that the magnetite in the banded ironstone of the Lower

Griquatown Stage was not formed as a result of the metamorphism of pre-existing hematite or siderite.

The characteristic euhedral and subhedral outlines of the magnetite, pyrite and carbonate present in the banded ironstone, and their distribution in well-defined layers or as disseminated crystals in layers of silicate or chert, indicate that the magnetite, pyrite and carbonate are not of detrital origin, but that they either crystallized in situ or that they crystallized in the water of the basin of deposition and then settled down on to the floor of the basin. The mode of occurrence of the crystals of carbonate in the banded ironstone indicates that both these processes did, in fact, take place. There can be no doubt that the small crystals of carbonate in the Lower Shale Beds, described on page 52, and illustrated on Plate IX (a), crystallized directly from the material in solution, and then settled on to the depositional interface with little or no disturbance of the bedding. On the other hand, the crystals of carbonate which contain cores of chert, and which lie in chert bands in the Banded Ironstone Zone, as described on page 38, and illustrated on Plate VI (a), appear to have been formed in situ by the crystallization of carbonate-bearing solution trapped with the silica when the latter was precipitated as a colloid.

Du Preez (1944, p. 324) found that many magnetite crystals in the banded ironstone at Thabazimbi had, in their centres, inclusions of minerals present in the layers in which the magnetite crystals lay. He concluded that this material was enclosed by the magnetite crystal during its early stages of crystallization, but at a later stage similar material was forced out by the grain's force of crystallization which, according to Harker (1939, p. 41) is "effective only when it is called into play by resistance as growth proceeds", and is also dependent on temperature. Consequently, even a mineral with a strong force of crystallization may show a core full of inclusions while the mantles may be clear. This is the case with the rhombs of carbonate described above, and the inclusions of quartz and small amounts of other minerals is consistent with its slow crystallization which commenced at an early stage in the rock's history.

The view that magnetite may be a primary mineral of major importance in sedimentary iron-bearing formations is supported by observations by Broderick (1920) and Gruner (1946) who showed that magnetite is the dominant mineral in the unoxidized and relatively unmetamorphosed Biwabik iron-bearing formation of the Mesabi Range, and by James (1954, p. 263), who states that "abundance of magnetite in rocks that are essentially unmetamorphosed, as indicated by the fine grain of the chert and the presence of such low-grade minerals as greenalite and minnesotaite, is a valid criterion that should serve to separate the primary magnetite rock from magnetite-bearing rocks that are products of later metamorphism".

Spiroff (1938, pp. 818 to 828) has shown by experiments in the laboratory that magnetite can be formed under atmospheric pressure and normal temperature, and that this magnetite has an X-ray diffraction pattern identical with that of magnetite found in nature. Friedman (1954, p. 101) cited examples from various localities to prove that authigenic magnetite has been formed from meteoric solutions under conditions of low temperature and low pressure. Brown (1943, p.147) reviewed the occurrence of low-temperature magnetite, and concluded that "magnetite has formed at a number of localities by natural supergene or superficial low-temperature processes", and that magnetite is formed in such situations when a favourable balance exists between oxidizing and reducing tendencies.

In a recent publication Huber (1958) developed an Eh-pH stability diagram for hematite, magnetite, siderite, pyrite and iron sulphide. (Fig. 2). Certain simplifying assumptions were made because of the numerous variables involved.

Discussing the effects of additional variables on the fields of stability, Huber (1958, pp. 131 to 136) stated that a change in the partial pressure of CO_2 would shift the position of a natural environment in the Eh-pH diagram but will not change appreciably the shape or position of the fields of stability of any of the minerals. For a shallow basin of deposition the effect of pressure on the boundaries of the fields of stability of hematite, magnetite and pyrite is probably unimportant.

The effect of temperature changes is so small that it may be neglected within the temperature and pressure range that is to be expected in the normal marine environments. In any system that has an appreciable quantity of dissolved salts, the activity co-efficients are relatively constant and the positions of the fields of stability of the various minerals will not be changed by small variations in salinity. However, it is instructive to note the changes in the stability diagram which would be brought about by changes in the concentration of the sulphide ions. Figure 3 illustrates the change in the diagram brought about by reducing the concentration of sulphide ions to that encountered in the water of rivers or lakes. Of special importance is the lowering of the upper limit of the pyrite field with a concomitant increase in the sizes of the siderite and magnetite fields. In view of the changes that can be made by assuming different values for one variable in the system, and because of the numerous variables involved, it is appropriate that the relative positions of the stability fields are stressed, rather than their absolute limits on the pH and Eh scales.

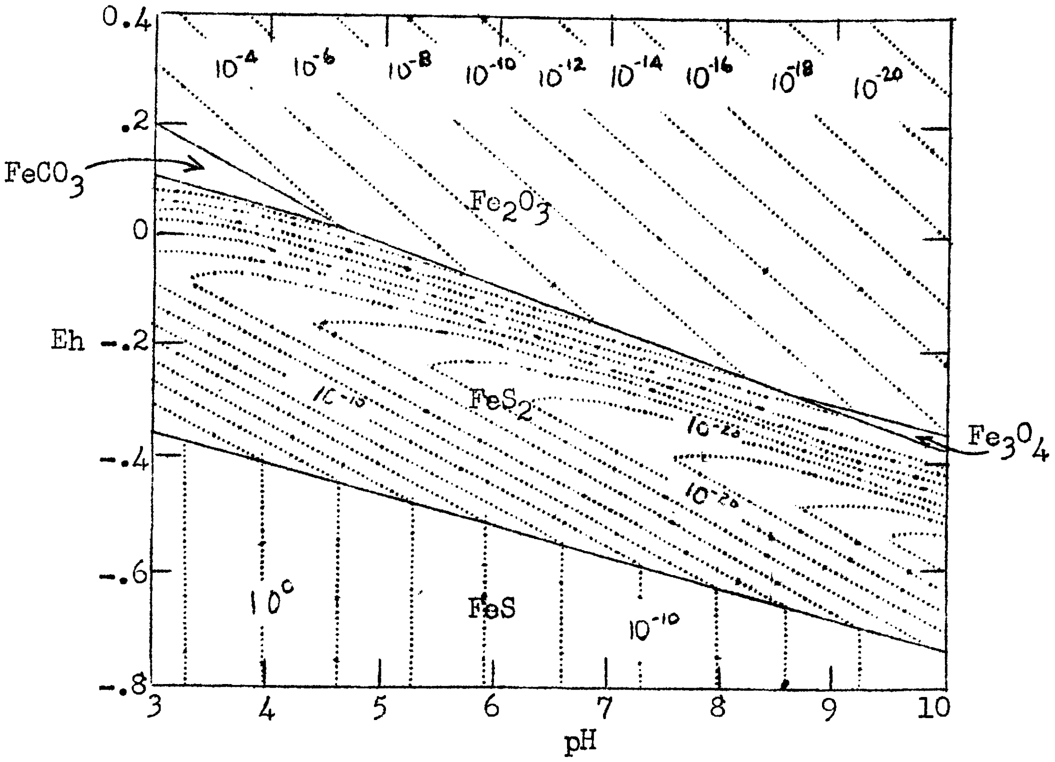


FIGURE 2.

Eh-pH stability fields for hematite, magnetite, siderite, pyrite and iron sulphide (FeS) in normal sea water system. Contours indicate the activity of the ferrous iron in equilibrium with the solid phases (expressed in mols per litre). (After Huber).

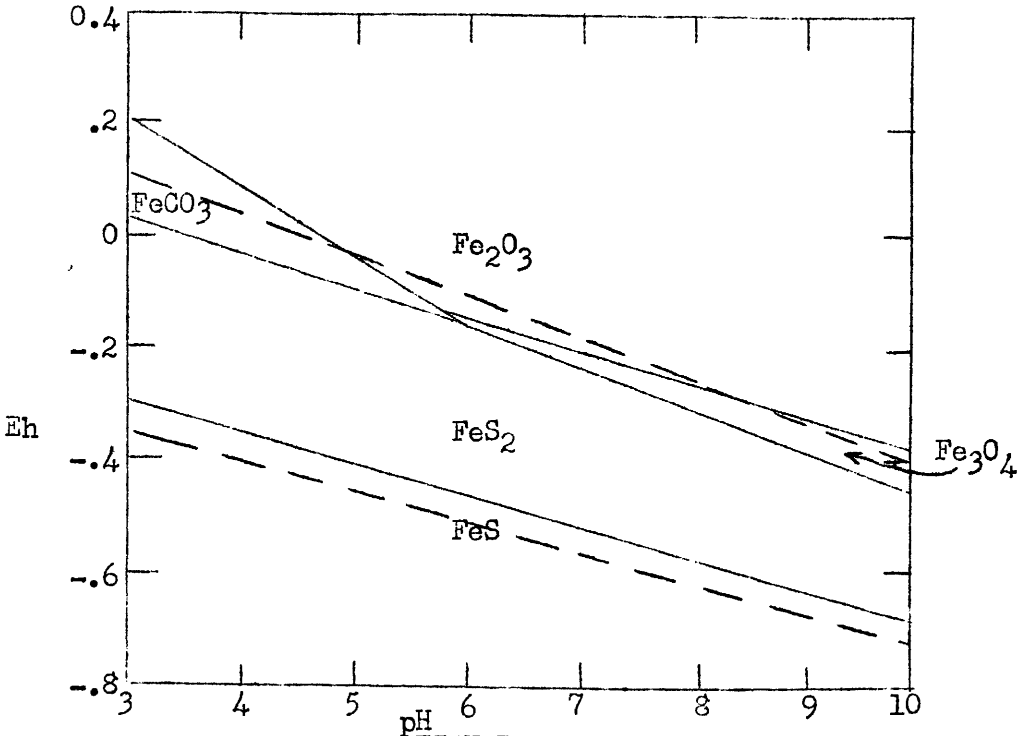


FIGURE 3.

Eh-pH stability fields for hematite, magnetite, siderite, pyrite, and iron sulphide (FeS) with carbonate equilibria as in normal sea water and total sulphur as in average river and lake water. Dashed lines for total sulphur as in normal sea water. (After Huber).

From the foregoing it is clear that iron entering the basin of deposition of the Lower Griquatown Stage could have been precipitated either as iron sulphide, or as iron carbonate, or as iron oxide, depending upon the Eh and pH of the water in the basin of deposition. It is also to be expected that some of the other ions entering the basin of deposition in solution will be affected by the change in the chemical environment.

Rankama and Sahama (1950, p. 198) explored the possibility of using the Eh and pH of a sedimentary medium as a framework for the classification of chemical sediments. Krumbein and Garrels (1952) used the same controlling factors in a slightly later classification with rather more emphasis on the iron-bearing formations. It is possible to subdivide various atoms and radicals into four groups on the basis of whether or not the solution or precipitation of chemical compounds in which they are contained is affected by the Eh and pH of their environment, as follows:-

1. Eh-and pH-independent group (e.g. Na^{+}, K^{+}, Ca^{++}, Mg^{++}, Cl^{-}, Br^{-}, I^{-}).
2. pH-dependent group (unaffected by Eh) (e.g. $CO_3^{=}$, $PO_4^{\equiv}$, OH^{-}).
3. Eh-dependent group (unaffected by pH) (e.g. Fe^{++}, Fe^{+++}, Mn^{++}, Mn^{+++}, Mn^{++++}).
4. Eh-and pH-dependent group (e.g. sulphide: sulphate, where the ratio of sulphide to sulphate increases with decreasing Eh and with decreasing pH, as can be seen from the following equation: $S^{=} + 4H_2O = SO_4^{=} + 8H^{+} + 8e$).

It follows, therefore, that it should be possible to deduce, from the assemblage of minerals in the banded ironstone of the Lower Griquatown Stage, under what conditions some of the minerals of this rock were precipitated from solution. For example, although Ca^{++} and $CO_3^{=}$ are independent of Eh, $CO_3^{=}$ is strongly dependent on pH.

An increase in pH tends to cause precipitation of calcite, whereas in an environment with a pH below a certain value calcite will not be precipitated.

Krumbein and Garrels (1952, p. 22) classified depositional environments into four major types, which probably show all gradations, as follows:-

1. Restricted arid (evaporite) environment: High salinity (greater than $200^{o}/_{oo}$). Eh positive, pH approximately 8 to 9.
2. Normal marine, open-circulation environment: Normal ocean salinity, Eh positive, pH approximately 7.5 to 8.4.
3. Restricted humid (euxinic) environment: Salinity slightly less than for (2) above, Eh generally negative, pH of the order of 7 to 8.
4. Peat-bog environment: Fresh-water, bog conditions, Eh negative, very wide pH range.

On this broad basis the authors constructed a diagram showing the fields of occurrence of the various mineral associations relative to the Eh-pH conditions of the environment during their deposition. (Fig. 4). The boundary at pH 7.8 is designated as the "limestone fence" because it is the approximate lower pH limit for the formation of abundant calcite. The zero Eh line is the "organic matter fence", and the other limits represent "fences" between certain oxides and carbonates, as well as sulphates and sulphides. The diagram is based on the assumption that the average composition of the sedimentary medium is like that of sea water, although the diagram is applicable over a wide range of salinity.

The field in the upper right-hand corner represents normal marine, open-circulation conditions. The field below this represents euxinic environments with partial stagnation. As the succeeding fields below this are encountered, the Eh becomes more

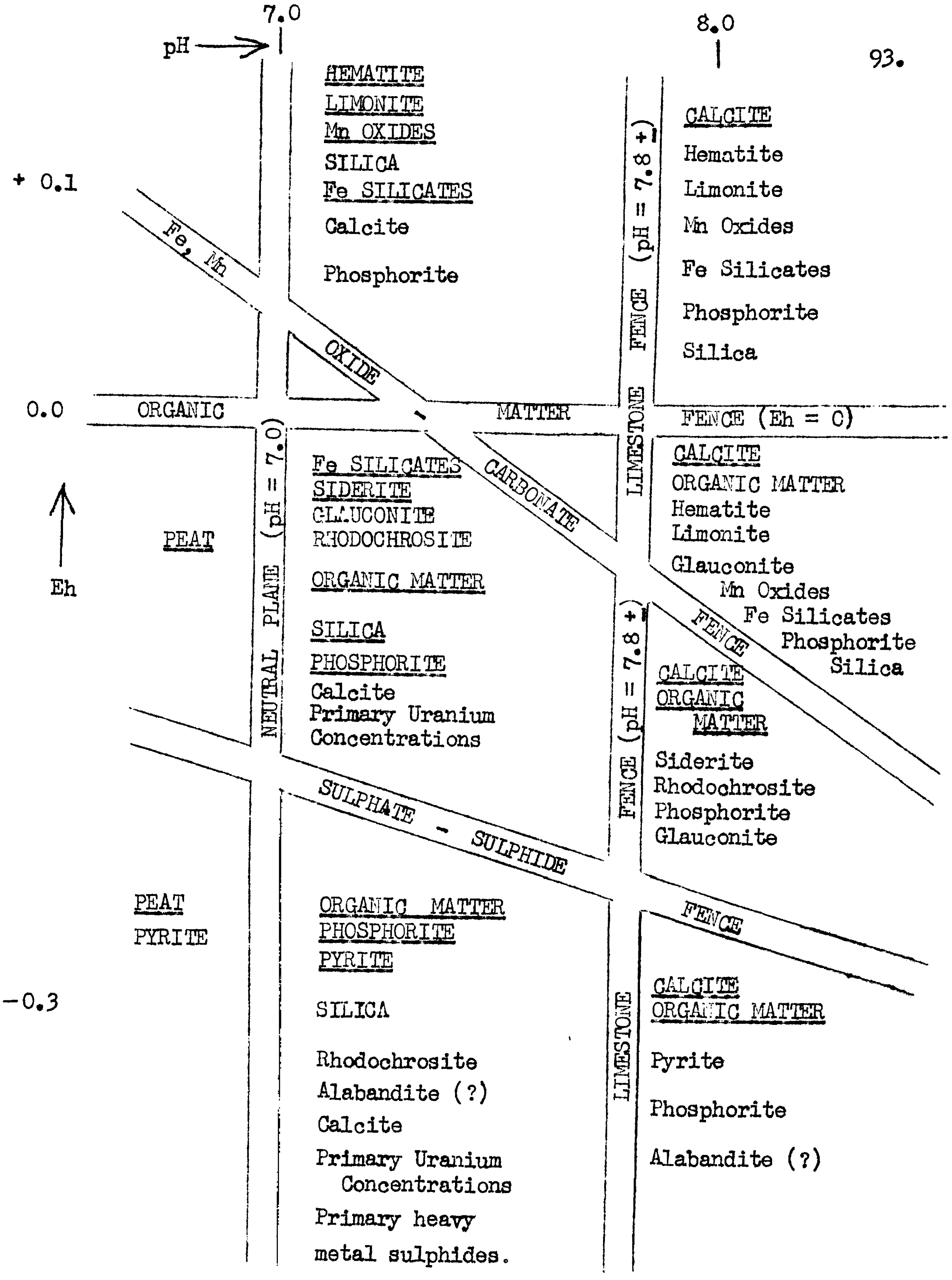


FIGURE 4.

Fields of occurence of various mineral associations relative to the Eh-pH conditions of the environment during their deposition.

negative, the amount of organic matter may increase, and primary pyrite becomes increasingly important.

In contrast with the fields located to the right of the limestone fence, chemical sediments formed in environments with pH between 7.0 and 7.8, tend to have calcite present as an accessory rather than as a dominant mineral. In the uppermost field of this group, with positive Eh values, the iron oxides and silicates predominate. As the Eh of the environment becomes negative, organic matter becomes more important and pyrite becomes abundant below the sulphate-sulphide fence.

The rocks of the Lower Griquatown Stage contain no primary calcite, but do contain iron oxide, iron carbonate, and iron silicates. Referring to the diagram of Krumbein and Garrels (Figure 4), it will be seen that such an association of minerals would be anticipated between pH values of 7.0 and 7.8, and Eh values near zero. According to the classification of depositional environments by Krumbein and Garrels given on page 92, these conditions may be expected in a restricted humid (euxinic) environment.

The presence of pyrite in the rocks near the base of the Lower Griquatown Stage already indicates that these rocks have been deposited in a restricted basin in which conditions were such that the Eh of the environment would be negative for short periods. According to Krumbein and Garrels (1952, pp. 3 and 5) the pH in a normal marine, open-circulation environment varies between 7.8 and 8.2 and the Eh varies between 0.1 and 0.4, whereas in a euxinic environment the pH is between 7.0 and 8.0, and the Eh between - 0.3 and 0.1. It may therefore be concluded that the material in solution in the water of the rivers was not contributed directly to the open sea, but that a restricted basin of deposition must have existed between the shore and the open sea. This condition would be satisfied if one were to postulate a low, off-shore buckle in the sea not very far from the shore-line. As a result of this buckle, a long, shallow, restricted basin would be formed, and the environmental conditions in this basin would have been ideal for the deposition of chemical sediments of the banded ironstone type. Conditions essentially similar to those proposed above were also suggested by James (1954, pp. 276-281) to account for the formation of the Precambrian banded iron-bearing rocks in the Lake Superior region.

Primary pyrite is found only in the lowermost portion of the Lower Griquatown Stage, where layers of pyrite alternate with layers of magnetite, carbonate and silicate. It is clear, therefore, that the Eh-pH conditions in the basin of deposition were such that a small variation of the Eh or pH would cause the precipitation of either pyrite or magnetite or carbonate. As shown in Figures 1 and 2, the solubility of iron decreases very rapidly with a small decrease in Eh or pH as soon as the boundary of the fields of stability between oxide and sulphide or carbonate and sulphide is crossed. Thus one would expect rapid precipitation of pyrite as soon as the Eh or pH of the environment decreased to below this boundary, but with a small increase in Eh or pH, rapid precipitation of pyrite will be replaced by slower precipitation of magnetite or carbonate.

As precipitation proceeded, there appears to have been a gradual increase of Eh, so that soon no more pyrite was precipitated. J. H. Genis (personal communication) recently made a detailed mineralogical study of the so-called "boornate" (referred to by Du Toit, 1945, p. 167) which are found in the Lower Asbestos Horizon in the Prieska area. He found that the fresh rock consists almost entirely of green ferrostilpnomelane, but that it weathers easily to brown ferristilpnomelane. In numerous specimens examined from higher up in the succession, some of which were obtained from depths of 3,000 feet below surface, the present writer found predominantly brown ferristilpnomelane. The higher ratio of Fe_2O_3 to FeO in the stilpnomelane as samples are taken progressively higher in the succession confirms the gradual general increase in Eh during the deposition of the Lower Griquatown Stage. This is in accordance with the slow filling of a shallow geosyncline, in which the rate of sedimentation exceeds the rate of subsidence. Slight fluctuation in Eh or pH caused alternate layers of predominantly carbonate or predominantly oxide to be precipitated. Colloidal silica and iron silicates, the deposition of which is essentially independent of Eh and pH, were precipitated simultaneously with either iron carbonate or iron oxide, or in layers of pure silicate.

Chemical precipitation continued over a long geological period, until all the material that was to form the Banded Ironstone Zone in the Abramsdam Syncline, and the Banded Ironstone Zone and the greater part of the Banded Jasper Zone in the regions farther north, had been deposited.

The period of true chemical deposition now gradually gave way to a period of increasing mechanical sedimentation, probably as the result of a slow rising of the ancient land surface relative to the basin of deposition. At first only very fine clastic material was brought into the basin with the material in solution. Finely-banded shale was gradually replaced by an extremely fine-grained mudstone in which all the minerals characteristic of the underlying banded ironstone are still present in ever - decreasing amounts. Eventually mechanical sedimentation became predominant and small, angular, clastic grains of quartz, feldspar and mafic minerals were washed into the basin of deposition in large amounts. Some of these minerals, for example quartz, and to a lesser extent, feldspar, which are resistant to secondary alteration, have been preserved with little change and are still clearly visible in thin section (Plate IX (b) . However, the mafic minerals, which are particularly sensitive to chemical attack, were much altered, so that it becomes practically impossible to say how much of the chloritic material now present in the rock is a primary chemical precipitate, how much of it is unaltered detrital material, or how much of it had been formed during diagenesis of the rock.

Following the deposition of the Lower Mudstone Beds in the Abramsdam Syncline, it would appear that the water in the basin of deposition became deeper once more, probably as a result of subsidence of the basin of deposition. This is indicated by the presence of a thin layer of chert with an intraformational conglomerate or breccia, which lies immediately above the Lower Mudstone Beds. The chert layer is a chemical precipitate with a mineralogical composition similar to that of the rock of the Banded Ironstone Zone, including the presence of crocidolite. After this short period of chemical precipitation, the depositional sequence outlined above was repeated with the eventual formation of the Upper Shale Beds and Upper Mudstone Beds.

The deposition of the Lower Griquatown Stage was completed with the deposition of the tillite, probably by ice-floes floating into the basin of deposition (Du Toit, 1954, p. 556), and this was followed by the eruption of the andesitic lava and tuff of the Ongeluk Stage, and the intrusion of the associated sheets of diabase into the Lower Griquatown Stage. The eruptions were in part subaqueous, as indicated by the interbedding of siliceous sediment and the development of pillow-structures.

D. THE ORIGIN OF THE BANDING

Wagner (1928, p. 65) stated that no satisfactory theory had been advanced to explain how thin alterations of carbonate and cherty or shaly material came to be precipitated repeatedly. He suggested that, assuming that the silica was in colloidal solution in the sea water and that the iron was directly contributed to the ocean by magmatic waters, then a possible explanation of the phenomenon is suggested by certain of Liesegang's experiments on rhythmic precipitation. Banded ferric hydroxide and silica can be produced in the laboratory by Liesegang's method (diffusion of a soluble hydroxide into a silica gel previously impregnated with a soluble iron salt), but this method does not seem to be adequate to explain the extensive banded iron-bearing formations of the Precambrian, and the difficulties in applying this explanation become practically insurmountable if the material from which these formations were formed was derived entirely from the weathering of pre-existing rocks.

Moore and Maynard (1929, pp. 518-520) carried out experiments with mixtures of colloidal silica and ferric oxide, ferric hydroxide or ferric bicarbonate, stablized by organic matter. They found that ferric hydroxide was precipitated before the silica and that the contact between the precipitate of ferric hydroxide and the silica was quite sharp , but that the upper surface of the gelatinous silica was irregular. When a fresh supply of material was added, a new layer of ferric hydroxide was deposited on the gelatinous silica. The ferric hydroxide first filled the irregularities and cavities on the upper surface of the silica and then formed a definite layer. They concluded that bands of silica and ferric hydroxide could be formed in nature by this process, provided a periodic supply of silica and iron is available.

It has been shown on page 95 , that layers of varying composition will be precipitated as a result of changes in Eh and pH in the basin of deposition. The most probable explanation for these changes is that they are due to seasonal fluctuations in climate and rainfall, which would, in turn, also affect biochemical processes. Cooper (1935, pp. 419 - 438) measured a rhythmic seasonal change in the pH of the English Channel which is not directly related to stream flow. He also found (1937, pp. 299-307) that the Eh in sea water is dependent only on the partial pressure of oxygen and the pH of the sea water, but is not particularly sensitive to the amount of dissolved oxygen. Many factors could give a rhythmic alteration of pH, the simplest perhaps would be the seasonal variation in river flow, causing a lowering of pH of the basin of deposition when it is receiving large amounts of river water during the rainy season, and an increase of pH in dry seasons when little or no river water enters the basin of deposition.

Alexandrov (1955, pp. 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 concluded that, owing to seasonal changes of temperature, rainfall, activity of organic matter, and pH, the Precambrian soil yielded alternately solutions carrying to the basin of deposition almost exclusively silica during the warm season and chiefly iron oxide during the cool period of the year. The seasonal environment favourable for the intermittent leaching of iron oxide and silica may be summarized as follows:

<u>Warm Season</u>.	<u>Cool Season</u>.
(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.
Lateritization of soil.	Podzolization of soil.

The intermittent introduction of solutions containing predominantly either compounds of iron or of silicon into the basin of deposition naturally would simplify further the process of selective precipitation within the basin.

Three types of irregularities are present in the banding of the finely laminated banded ironstones.

The first type was formed as a result of most irregular small-scale crinkling of the banded ironstone, with resultant local pinching and swelling of individual layers (Plate I (a) 3). There was no fracturing of the material, but small drag-folds, knots and lenses were formed. These structures are restricted to the lower part of the Banded Ironstone Zone, and were caused by thixotropic changes in the colloidal material and flowage of the material under the influence of gravity down the slope, possibly aided by currents and slight movements of the sedimentary floor. This type of deformation thus represents true primary folding and should not be confused with the numerous, small drag-folds present near the base of the succession of banded ironstone near Postmasburg, where this rock has been thrust over the Dolomite Series.

A second type of irregularity, also restricted to the lower part of the Banded Ironstone Zone, is the lenticular habit of some of the layers, even in strata where folding is practically absent. It would appear that these lenticles were formed as a result of minor undulations in the surface on which the material was deposited as well as a certain amount of subsequent differential movement of the plastic material in the layers due to the weight of the superincumbent strata.

The third type of irregularity is invariably associated with post-depositional folding of the strata, and is commonly encountered throughout the stratigraphic succession. That it is of tectonic origin rather than due to post-consolidation slumping is proved by the regional parallelism of the fold-axes. It consists of a series of fairly regular anticlines and synclines which range in amplitude from less than one millimetre to over ten kilometres.

In these folds a definite thickening of some layers has taken place in the crests of the anticlines and in the troughs of the synclines. In areas where only slight folding has taken place, eg. at the Pomfret Mine, the pinching and swelling of individual layers is only noticeable when individual layers are followed over appreciable distances, whereas in areas that had been affected by intensive Post-Waterberg folding, eg. in the workings on Leelykstaat, the variation in the thickness of layers has often been intensified and is easily recognized in the tight, often inverted, folds. It is especially marked in the seams of crocidolite.

Completely lithified banded ironstone is a hard, competent rock. However, no shattering took place during the Pre-Loskop folding, which indicates that the banded ironstone had not been indurated at the time this folding took place, and the pinching and swelling of the layers in the folds shows that at least some of the layers were still in a sufficiently plastic state for movement of material to take place within individual layers.

E. DIAGENESIS AND LITHIFICATION.

It may be expected that the conditions prevailing below the depositional interface after deposition of the material from which the banded ironstone of the Lower Griquatown Stage was formed, could exert a modifying influence on the minerals that crystallized ultimately. Modifications of this nature are best described under the heading of "diagenesis".

> Pettijohn (1957, p. 648) states that "the term diagenesis .... has been variously defined. All writers would exclude metamorphic changes from the domain of diagenesis, but as pointed out by Deverin (1924), no distinction between diagenesis and metamorphism is possible. Diagenesis is, in fact, the beginning of metamorphism because it leads to modification of the textures, structures, and mineral composition of a sediment. Such modifications are the earmarks of metamorphism according to Grubenmann."

Pettijohn (idem) also states that in sediments consisting of a mechanically transported fraction and a chemically precipitated fraction, there is no *a priori* reason why such materials should be in chemical equilibrium with one another. Under proper conditions, such as a rise in temperature or in the presence of a suitable medium, reactions between the several phases present may take place. These reactions are diagenetic at the lower temperatures and pressures and metamorphic at more elevated temperatures and pressures. Correns (1950, p. 49) states that the changes, not caused by weathering, in a sediment between its sedimentation and metamorphism are characterized by the word "diagenesis", and that the borderline between diagenesis and metamorphism is arbitrary and a matter of usage of language. In this thesis the term *diagenesis* refers to the chemical reorganization of the deposited and precipitated material concurrent with compaction, under conditions of increased temperature and pressure brought about by the simple burial of the material. The term *metamorphism* is used to denote all the chemical and mineralogical changes that took place in the sediment as a result of influences from outside, eg. the intrusion of igneous material, and tensional or compressional stress associated with periods of folding.

Krumbein and Garrels (1952, pp. 20 - 23) attempted to explain certain anomalous mineral associations by assuming that the zero Eh surface, which in normal open-circulation environments coincides with the depositional interface, may rise above the interface under stagnant conditions. The water at the surface of the basin of deposition will then have positive Eh values, whereas the water at the bottom of the basin may have negative Eh values. Material precipitated near the surface of the water will therefore not be in equilibrium with the environment at the depositional interface, and replacement of this material, or its solution and reprecipitation in a stable form would be expected. Similar diagenetic changes may take place below the depositional interface owing to negative Eh conditions.

Zobell (1946, p. 484) emphasized that Eh is an intensity factor, and does not indicate the oxidizing or reducing capacity of a system any more than temperature indicates how many calories of heat it may contain. In banded ironstone where, for example, a large amount of iron oxide was precipitated relative to the amount of potentially reducing material, eg. organic matter, the total diagenetic effect by the process proposed by Krumbrein and Garrels cannot thus be large. Krumbein and Garrels (1952, p. 23) state that experience has shown that diagenetic effects of sufficient magnitude to mask the original Eh-pH conditions of sedimentation are rare among the bulk of common sedimentary rocks.

In the experiments described earlier, and in the discussions concerning the effect of Eh and pH during precipitation, the conditions concerned may be considered as those pertaining to an open system. However, once deposition has been completed and dehydration and crystallization commence, additional factors have to be considered.

Migration of material on a large scale is no longer possible, and only a finite amount of water and other material is present in the precipitate. The system thus becomes closed, and crystallization will proceed according to the chemical laws pertaining to these systems. Although much valuable information on closed systems of silicates has been obtained since the classic experiments of Bowen and Schairer in 1932, many problems are still unsolved. The recent paper by Flaschen and Osborn (1957) on the system iron oxide-silica-water at low partial pressures of oxygen, contains much information pertaining to the problem of the diagenesis of banded ironstone. They were able to synthesize fayalite, greenalite, minnesotaite and magnetite and to investigate their stability relations. An important feature of their work was the realization (idem, p. 933) that "in a closed system ... only negligible quantities of ferric oxide will form from magnetite by the dissociation of water before the oxygen partial pressure is lowered to the point that a magnetite-hematite equilibrium is attained".

Assemblages containing fayalite are only possible at temperatures below 250°C where no separate aqueous phase is present. The proportion of FeO and Fe_3O_4, as well as the presence or absence of other phases in a mixture of a given iron, silica or water content, is related to a specific range of partial pressure of oxygen, or of the ratio of the partial pressures of H_2O and H_2.

Flaschen and Osborn (idem, pp. 937 - 938) cite the example of an aggregate containing a high percentage of iron and water under low partial pressure of oxygen at a temperature of about 200°C. The assemblage will consist of greenalite with a low content of ferric iron and magnetite (plus water). However, as oxygen is added, this assemblage is changed progressively to greenalite with a high content of ferric iron plus magnetite, then to greenalite plus minnesotaite plus magnetite, minnesotaite plus magnetite, minnesotaite plus quartz plus magnetite, and finally to quartz plus magnetite. With further oxidation hematite appears as a phase.

This example calls attention to the fact that notable changes in the mineral assemblage of a mixture with a composition in the system $FeO-Fe_3O_4-SiO_2-H_2O$ are brought about by changing the oxygen level. If sufficient amounts of other components are present, for example alkalies and alumina, other phases, eg. stilpnomelane, will no doubt be formed, along with minnesotaite or even in place of it.

The fact that fayalite is absent in the banded ironstone of the Lower Griquatown Stage is of prime importance. There can be no doubt that a considerable amount of water was present in the material deposited to form these rocks. Fayalite is stable in the presence of an aqeous phase only at temperatures exceeding 250°C. It follows, therefore, that the banded ironstone of the Lower Griquatown Stage was never subjected to a temperature exceeding 250°C. Further evidence in support of this conclusion is submitted on page 110. In the Lake Superior region fayalite and grunerite are present in the eastern Mesabi Range, where metamorphism of a reasonably high grade has taken place, but are absent in the essentially unmetamorphosed rock of the western Mesabi Range, where the principal iron silicates are greenalite, minnesotaite and stilpnomelane.

From the foregoing it is clear that some minerals, eg. magnetite, may have been precipitated directly when the iron-bearing solutions entered the water of the sea, but that the same minerals could also have crystallized after deposition under conditions of increased temperature and pressure brought about by their burial. It is also possible that, during diagenesis, some of the minerals that were originally precipitated directly from solution may have recrystallized to form larger crystals, and that a small amount of movement of material could have taken place within individual layers. In other words, the process of primary crystallization grades imperceptibly into the process of crystallization or recrystallization during diagenesis.

Having thus deduced that all the minerals present in the rock of the Lower Griquatown Stage, with the exception of riebeckite and its fibrous equivalent crocidolite, could have crystallized, and probably did crystallize, either directly from solution or from a colloidal precipitate during diagenesis, and that the temperature of the rock never exceeded 250°C, one is forced to the conclusion that the riebeckite present in the banded ironstone was formed as a result of the same processes that formed the other silicates, eg.

stilpnomelane and minnesotaite, with which the riebeckite is intimately associated. The development of crocidolite, the fibrous variety of riebeckite, is discussed on pages 119 to 132.

From the mineral relationships in the fresh rock certain conclusions may be drawn regarding the order of crystallization. Mention has been made on page 87 of the small carbonate crystals which had crystallized directly from the water and had settled to the surface of deposition, and also of the rhombs of carbonate with cores of chert that had crystallized from the solution trapped in layers of colloidal silica. As these layers became dehydrated, shrinkage-cracks were formed approximately perpendicular to the bedding planes, but they were soon filled by less dehydrated material. (Plates VII (a) and (b)). The shrinkage-cracks cut through thin layers of magnetite, which may even be pushed aside by the material moving into the cracks, as illustrated in Plate VII (a). Many of the needles of amphibole grew from the layer of silica into shrinkage-cracks filled with silica without disturbance, and must therefore have crystallized after the cracks were formed. Needles of riebeckite which grew in the shrinkage-cracks tend to radiate from the edges of thin layers of magnetite (Plate VII (b)), which is in accordance with the tendency of riebeckite needles and laths to grow from initiating surfaces of magnetite, where possible, as described on page 38 and illustrated in Plates VII and VIII. It is clear, therefore, that the magnetite crystallized before the needles of amphibole.

In the literature dealing with the Lower Griquatown Stage, magnetite has always been considered to have crystallized during metamorphism of the rock, whether this was thermal (Du Preez) or dynamic (Du Toit). The fact that it has now been established that, even in essentially unmetamorphosed banded ironstone, magnetite is primary and was one of the first minerals to crystallize, is of great significance, as discussed in Chapter IV.

Needles of amphibole, whether radiating from grains or layers of magnetite, or dispersed through bands of chert, persist through individual crystals of quartz. It appears probable, therefore, that the well-interlocking, clear crystals of quartz were formed by recrystallization of an earlier form of silica. It is not possible to state with certainty what the early crystalline state of the silica was, but it was presumably opaline or chalcedonic. In this connection the embayment of the grains of clastic quartz in the green mudstone, and the presence of microcrystalline quartz intimately associated with the chloritic material in the surrounding matrix is of interest. James (1951, pp. 260 - 216) described similar phenomena in the graywacke in the Iron River District, Michigan. He concluded that the clastic quartz as well as the chemically precipitated silica had been replaced to a greater or lesser degree by chlorite during diagenesis, but prior to the crystallization of the silica to its present form, because generally at least 50 per cent of the chemically precipitated material is replaced whereas the clastic material is only slightly embayed.

The lithification of the banded ironstone may be viewed as a long, continuous process which took place under slowly changing conditions, during which the mineralogical composition was reorganized continuously in an attempt to maintain equilibrium. Movement of material during crystallization was insignificant and confined to the limits of individual layers.

F. METAMORPHISM.

1. Regional Metamorphism.

Many descriptions of the rocks of the Lower Griquatown Stage may be found in the literature, but very little petrological information has been published and no detailed examination on unweathered rock has been made in the past. However, it is generally accepted that the rocks have undergone appreciable metamorphism since deposition.

In a discussion of the origin of crocidolite, Vermaas (1952, pp. 228 - 229) concluded that two different types of metamorphism had operated at different times. Tabular riebeckite was formed during early thermal metamorphism, but became unstable under conditions of shearing stress during later dynamic metamorphism and was recrystallized to crocidolite. In support of his hypothesis Vermaas (idem, Plate XXXIII, Fig. 2) included a photograph of a sample from the Carn Brae Mine, near Prieska, in which crocidolite appears to grow from the sides of an asbestos seam inwards at the expense of tabular riebeckite. The present writer has frequently visited the Carn Brae Mine, which was re-opened by Cape Blue Mines (Pty) Ltd. in 1957, and has seen numerous samples identical with the one illustrated by Vermaas, but they are only found adjacent to dykes. Similar samples may be obtained where any asbestos seam is cut by a dyke anywhere on the Cape asbestos fields. Vermaas is therefore correct in calling the riebeckite a "tabular thermal metamorphic amphibole", but this riebeckite was formed exclusively as the result of local thermal metamorphism adjacent to dykes. Furthermore, layers of massive riebeckite adjacent to dykes have also undergone recrystallization to tabular riebeckite. As a result of these observations, Vermaas' conclusion that the banded ironstone was subjected to general thermal metamorphism prior to the formation of crocidolite, cannot be accepted.

Du Toit (1954, p. 158) states that the rocks were much metamorphosed during the Post-Waterberg movements with the development of new minerals, and, more specifically (1945, p. 162), that the rocks were formed by "repeated transformation or polymetamorphism of ferruginous sedimentary rocks of a unique kind under peculiar circumstances." The present writer cannot accept Du Toit's conclusions. Reasons for his disagreement are given below.

The rocks of the Lower Griquatown Stage contain chlorite, iron-bearing carbonate, minnesotaite and stilpnomelane. This indicates that the rocks were not subjected to extensive thermal metamorphism. According to James (1955, pp. 1455 - 1488), the above mineral assemblage is found in the Lake Superior region only in rocks of the chlorite and biotite zones of low grade metamorphism. These minerals are absent in rocks where the metamorphism was of a higher grad
In the garnet and staurolite zones grunerite, hornblende and garnet are found, and pyroxene is present only in the sillimanite zone of highest grade. Grunerite, garnet and pyroxene were not found in the rocks of the Lower Griquatown Stage. James (idem) found that magnetite and hematite may be present in all zones of metamorphism.

From the mineral assemblage of the rocks of the Lower Griquatown Stage, it could be inferred that the banded ironstone had been subjected to a slight degree of thermal metamorphism. On the other hand, it has already been shown on pages 79 to 107 that pyrite, siderite, chlorite, magnetite, minnesotaite and stilpnomelane could already have formed in the banded ironstone by primary crystallization or during diagenesis. Under thermal metamorphism of low grade no new minerals could be expected to be formed and most of the metamorphic energy would be expended in coarsening the grains of the minerals already present. The greatest average diameter of the quartz grains in unweathered layers of pure chert in the Lower Banded Ironstone Beds is 0.08 mm. This value decreases in specimens taken from higher in the succession. If the banded ironstone had been subjected to extensive thermal metamophism, the crystals of quartz would have been larger. This conclusion is supported by the observations made by James (1955, pp. 1455 - 1488) in the Lake Superior region, where he found that the average diameter of the quartz grains increases in units of approximately 0.05 mm. per metamorphic zone from practically zero in unmetamorphosed rock to 0.10 mm. at the boundary between the biotite and garnet zones, and 0.20 mm. at the boundary between the staurolite and sillimanite zones.

James (1955, p. 1485) included a diagram, slightly modified from Rosenqvist, which indicates the pressure-temperature positions of the principal metamorphic zones calculated from thermodynamic information. Rosenqvist's conclusion that pressure plays but a small role to depths of 10 kilometres or more appears to have been confirmed by subsequent experiments in the laboratory. From this diagram the temperature represented by the boundary between the chlorite and the biotite zones at a depth of 5 kilometres would be 200°C or less. This figures agrees remarkably well with that already arrived at on page 105.

From the above it is clear that all available evidence indicates that the minerals in the Lower Griquatown Stage were formed by crystallization during deposition and diagenesis with lithification. The increased temperature and pressure developed was due mainly to the weight of the superincumbent strata. Thermal metamorphism was practically absent, except possibly in so low a degree that its effects would be indistinguishable from those of normal diagenesis.

The intensely folded nature of the banded ironstone in many regions in the Northwestern Cape proves beyond doubt that crustal deformation has taken place on a grand scale. Apart from the small amount of contemporaneous deformation during deposition, described on page 100, it is known that the banded ironstone of the Lower Griquatown Stage was subjected to two periods of folding. Visser (1944 and 1957) stated that after the deposition of the Pretoria Series but prior to the deposition of the Loskop System in the Northern Cape, the crust was compressed mildly from the west and the thinly bedded members of this Series were folded in broad and open synclines and anticlines, striking north-south. He found no evidence that the Loskop System was deformed prior to the deposition of the Matsap Formation (which is correlated with the Waterberg System of the Transvaal), but the beds of both these Systems, as well as those of the Pretoria Series, were folded and faulted extensively after the deposition of the Matsap Formation, but before the deposition of the Karroo System. It has therefore been established that the folding described by Du Toit (1945, p. 197) as "Pre-Matsap" had already taken place before the deposition of the Loskop System.

It has already been shown that the temperature in the normal banded ironstone never exceeded 250°C. Thus, even during the Post-Waterberg period of intense crustal deformation, the increase in temperature as a result of this deformation was too small to cause the formation of new minerals. As a result, the only effect that the tectonic movements could have had on the rock was the reorientation of minerals that had already crystallized. Microscopic examination of numerous samples of highly contorted banded ironstone revealed no obvious preferred optical orientation of the crystals of quartz or carbonate. As a rule there is also no preferred orientation of the needles of riebeckite in the bands of chert or of the other silicates in the rock. However, in some samples microscopic examination showed that the riebeckite needles and laths are distinctly orientated parallel to one another. Occasionally some crystals of quartz are elongated in the same direction, but there is no marked preferred optical orientation of the crystals. (Plate VI (c)). The riebeckite crystals may be orientated at any angle to the bedding-planes, and this angle may change frequently within the limits of a single thin section, so that the riebeckite assumes a wavy appearance with the waves more often than not approximately parallel to the bedding-planes. In hand-specimen these bands, especially when thin, show some resemblance to crocidolite, and are often referred to as "slip-fibre", a term which is misleading as the riebeckite is platy and brittle in contrast with the delicately fibrous habit of crocidolite. The riebeckite crystals in the rock layers immediately above and below the so-called "slip-fibre" bands often show no preferred orientation. There can be little doubt that the parallel orientation of the riebeckite laths in the "slip-fibre" bands described above was the result of re-orientation during folding.

Mention has been made on page 40 of a second type of "slip-fibre": thin layers or veins of riebeckite laths, with parallel orientation, found alongside small faults through massive riebeckite rock or in shear-zones which may cut across the bedding at any angle. The parallel orientation of these laths is clearly the result of stresses in the rock after it had been lithified and was no longer capable of yielding by folding. The age of these shear-zones is immaterial and could even be fairly recent.

In areas that have been subjected to intense Post-

Waterberg deformation, eg. on Koegas, the fibre in some of the seams of asbestos is inclined at angles of up to 45 degrees to the bedding-planes, and in exceptional cases to even smaller angles. Bending of the fibres in some seams is not unusual, and in some seams of crocidolite the fibres are perpendicular to the bedding-planes on one side of the seam, but bend over until on the other side of the seam they lie parallel to the bedding-planes. In rocks containing steeply inclined seams of fibre, shearing effects parallel to the bedding-planes are clearly discernable and veinlets of quartz lying perpendicular to the bedding have often been displaced for distances ranging from a fraction of a millimetre to a few centimetres. Similar effects may be seen in seams of fibre in tightly folded rocks. It is instructive to note that the direction of inclination of the fibres is in opposite directions on the two flanks of the folds. (Plate III (b)). It is clear that the inclination of the fibres was caused by movement, in the plane of the bedding, of the rock above the seam of fibre relative to the rock below this seam after the crocidolite had already crystallized.

To summarize: during the gentle Pre-Loskop folding, minerals that had already crystallized or were in the process of crystallization, were orientated parallel to the direction of least pressure. Relief of pressure took place by plastic deformation and migration of material within single layers before any appreciable stresses could be set up. When the rock finally crystallized completely, the pressure had been relieved and its effect left no record in the orientation of the later crystals. It would appear that the crocidolite crystallized after the Pre-Loskop folding had taken place, but before the period of intense Post-Waterberg folding. Further reorientation of some minerals took place during Post-Waterberg deformation and alongside faults and in shear-zones of later age. No new minerals were formed as a result of folding or faulting during any period, and the banded ironstone of the Lower Griquatown Stage does not appear to have been subjected to extensive thermal metamorphism. Even in highly folded areas, the total effect of regional metamorphism is therefore negligible.

2. Contact-metamorphism.

The metamorphic effects of dykes and sills on the rocks of the Lower Griquatown Stage are clearly visible with the naked eye. The "burning" effect due to the intrusion of dykes is easily recognized in asbestos reefs as they approach the dykes. However, the total thickness of the whole succession of banded ironstone exposed in underground development is small. Likewise, the metamorphic effects of sills on the strata adjacent to them are obvious in cores from holes drilled by diamond-drill, but here the lateral extension of single layers exposed is minimal. The mineralogical changes in the banded ironstone as a result of igneous intrusions were not studied in detail, as they are beyond the scope of this work. However, the effects of igneous intrusions on the asbestos fibre are of appreciable economic importance and are detailed below.

a. Metamorphism by Sills.

Wasserstein (Truter et al, 1938, p. 68) suggested that the injection of sills may have had an additive or "reinforcing" effect on crocidolitization. This aspect was discussed by Du Toit (1945 , pp. 188 - 189), who concluded that many of the sills are older than the asbestos, and could therefore have had no effect on crocidolitization.

There appears to be little doubt that most of the sills in the banded ironstone of the Northwestern Cape are related to the Ongeluk Volcanic phase, and were therefore intruded into the Lower Griquatown Stage before the crystallization of all its constituent minerals had been completed, although many of the layers may already have been lithified to a considerable extent. However, it is to be expected that the local increase in temperature as a result of the intrusion of the sills would have caused earlier crystallization of the material adjacent to them, and metamorphic minerals of a higher grade could be expected near the sills. Microscopic and X-ray investigation of samples taken near sills showed that the rock consists of the same minerals found in the normal banded ironstone, but that the average grain-size is appreciably larger and the banding less distinct. The appearance of a sample of shale taken 3 feet above the Hanging Wall Marker Sill at a depth of 444 feet below surface is illustrated in Plate IX (c). The rock consists of unorientated laths of minnesotaite, and euhedral to subhedral crystals of magnetite. The X-ray diffraction-pattern of this sample is identical with that of similar rocks that had not been metamorphosed. It is interesting to note that the grains of minnesotaite are more than five times as large as in the equivalent unmetamorphosed rocks, but that the crystals of magnetite are not appreciably larger. It is also seen that the magnetite crystals have been pushed aside by the growing minnesotaite crystals, weakening the normal sharp, finely banded appearance of the rock. This would indicate that the magnetite crystals had been formed prior to and not as a result of the intrusion of the sills, and also that the magnetite did not recrystallize as a result of the intrusion of the sills. This confirms the observations made on pages 38 and 106 regarding the early crystallization of magnetite.

Du Toit (1945, p. 189) stated that he had not found a crucial case where a sill cuts obliquely across a reef of asbestos. The present writer has discovered only one locality where this has actually taken place, viz. on the eastern flank of the Weilbach Syncline on the farm Koegas. Here a sill, about 25 feet thick, lies

32 feet below the Outer Reef where the trough of the Weilbach Syncline is exposed on surface. As the sill is followed northwards along the eastern flank of the syncline, it cuts obliquely across and upwards into the succession so that after one mile it now lies in the position of the Outer Reef. As the Third Outer, Second Outer and Outer Reefs were followed in the mine from south to north, it was found that each reef became poorer as the thickness of the intervening rock between the sill and the reef decreased, until eventually no fibre was developed at all in the position where the reefs are usually present. This sequence of events is to be expected where a sill intruded into the banded ironstone prior to the crystallization of the asbestos. The process of crystallization of the material adjacent to the sill would be accelerated by the abnormal increase in temperature of the material as a result of the heat emanating from the intrusive rock. Unless the temperature of the material is elevated to more than 250°C, no new minerals would be formed, but, as described earlier, the minerals grow to abnormally large size and primary banding is disrupted. Under these conditions the amphibole parent-material present in the rock crystallized into unorientated crystals and the asbestiform equivalent, crocidolite, is absent.

This example indicates that, at least in the Koegas-Westerberg mining-area, the intrusion of sills into potential asbestiform material prior to the crystallization of the asbestos did not have an additive effect on crocidolitization, but rather that these intrusions effectively prohibited the formation of amphibole asbestos.

b. Metamorphism by Dykes.

As all dykes in the Koegas-Prieska area cut through all the folds in the Lower Griquatown Stage, they are certainly of at least Post-Waterberg age. That they were also intruded after the crocidolite had been formed is clear from the "burning" effect on the fibre mentioned earlier.

As an asbestos band is followed towards a dyke, the fibre with its characteristic chatoyant lustre and silky appearance gradually gives way to bright, shiny, tabular riebeckite crystals. A typical example from the Carn Brae Mine has been illustrated by Vermaas (1952, Plate XXXIII, Fig. 2). Under the microscope it is seen that the tabular riebeckite crystals have grown at all angles to the direction of the c-axes of the crocidolite which they have replaced. The distance to which the asbestos has been destroyed on both sides of dykes is variable, and may be greater on one side than on the other. In near-vertical dykes the general rule is that the burning effect is approximately equal on both sides, and on either side the fibre has been completely destroyed up to a distance of approximately one quarter of the width of the dyke.

Metamorphic changes noticed in the banded ironstone adjacent to dykes include the development of green biotite and occasional large crystals of pyroxene. Fresh samples could not be found of the material identified by Du Toit (1945, p. 175), as acmite. The metamorphism of the banded ironstone as a result of the intrusion of dykes is beyond the scope of this thesis, but it is hoped to present details of some of the unusual mineral assemblages present in these rocks at a later date.

IV. THE AMPHIBOLE ASBESTOS.

A. THE ORIGIN OF THE AMPHIBOLE ASBESTOS.

1. General.

A review of the literature dealing with chrysotile shows that there are so many fundamental differences between the mineralogy and the mode of occurrence of chrysotile and amphibole asbestos that it is not surprising that none of the various hypotheses regarding the origin of chrysotile are directly applicable to amphibole asbestos. Similar conclusions were reached or implied by Hall (1918, 1930), Peacock (1928), Du Toit (1945), and others. The various theories regarding the origin of chrysotile have recently been summarized by Van Biljon (1959), and repetition is unnecessary.

That amosite and crocidolite were formed contemporaneously, and that conditions for their formation were identical, is proved beyond doubt by their intimate association (including the amosite-crocidolite "doublets" and "triplets") in the asbestos fields of the Transvaal. In the Koegas-Prieska area a horizon of prieskaite is developed between two horizons of crocidolite, as described on page 46. The mode of occurrence of the prieskaite is identical with that of crocidolite, and it is found in a similar country-rock. These facts indicate that this type of amphibole asbestos was also formed by the same processes as amosite and crocidolite. It is therefore possible to treat together the origin of all the types of amphibole asbestos occurring in typical cross-fibre seams interstratified with the banded ironstone of the Lower Griquatown Stage.

Crocidolite is the fibrous form of its chemically identical but physically different counterpart riebeckite, just as amosite is the fibrous form of grunerite, and prieskaite is the fibrous form of actinolite. In Chapter III it has been shown how the material required to form the rocks of the Lower Griquatown Stage came to be precipitated, and on page 83 it was concluded that the parent-material from which riebeckite was formed was precipitated in a colloidal condition. The only question to which an answer is outstanding is why the amphiboles are present in the banded ironstone of the Lower Griquatown Stage both in fibrous and non-fibrous forms.

2. The Development of the Fibrous Varieties of Amphibole.

Hall (1918) first suggested the possibility of asbestos originating from sediments without the direct action of igneous intrusions. His theory, essentially unchanged, was somewhat more elaborately treated in the second edition of his Memoir (1930, pp. 235 - 263). He concluded that the soda in the crocidolite was an original constituent of the banded ironstone, but that the magnesia was brought into the ironstone in solution by waters circulating from the underlying Dolomite Series. Under "load-metamorphism" the material present in certain layers in the ironstone was converted into unorientated crystals of amphibole, which he called "potential or incipient mass-fibre crocidolite". Hall (1930, p. 258) concluded that cross-fibre resulted from the recrystallization of the "mass-fibre", as

> "in a mineral like amphibole with its tendency towards a prismatic habit, the crystals are likely to assume a more or less elongated habit. These needles which are orientated more nearly at right angles to the bedding-planes may be expected to exert a certain amount of pressure against the containing walls, since it seems well established that crystals can exert a considerable pressure during growth".

The remaining material would then tend to crystallize parallel to the crystals which are pushing apart the walls.

How such a process could result in fibres orientated normal to the bedding is not clear. Peacock (1928, p. 278) summarizes the objections to this theory thus: "Hall's explanation appears to rely at once on the power of a crystal to grow against mechanical resistance, and on the tendency for crystals to grow in the direction of least obstruction." Under the conditions postulated by Hall, it would appear more likely that the riebeckite needles would tend to grow parallel to the bedding rather than perpendicular thereto.

Bryant (1925, pp. 565 - 566) felt that not enough stress had been laid on pressure. He considered the possibility that vast quantities of limestone had been eaten away in the Dolomite Series, and that the ironstone sank gradually into these cavities and thus assumed their present contorted appearance. Water and steam at high temperature, charged with magnesium, calcium and possibly sodium from the dolomite rose for a certain distance through the sediments, which Bryant considered to be porous, and, when the compositions and conditions were right, asbestos separated out, and the porous shale or mudstone was changed into hard jasper. In the light of our present knowledge, Bryant's theory is clearly untenable.

Observations regarding the association of asbestos with folds influenced Visser (1944), Du Toit (1945) and Vermaas (1952) to attribute the fibrous growth of asbestos to conditions of stress created during earth movements.

Peacock (1928, pp. 279 - 282) concluded that crocidolitization was a mild, static, non-additive, metamorphic process resulting in the chemical union, along soda-rich bedding-planes, of the necessary constituents already present in the ironstone. Chemical analyses led him to believe that crocidolitization is accompanied by a progressive loss of water through the walls of the seams. The change from the massive to the fibrous condition would thus take place first at the contacts of the seams with their walls, where the crystals would rearrange themselves normal to the controlling wall-surfaces. Where possible, accretion of crystals takes place in optical continuity with existing crystals, thus determining the orientation of the crocidolite fibres. Peacock believed that the transverse orientation of the fibres was brought about after crocidolitization was virtually completed. In Chapter II of this thesis descriptions have been given of the occurrence of numerous persistent bands of massive riebeckite of varying thicknesses, often intimately associated with crocidolite asbestos, eg. the "Blue Bank" in the Westerberg Asbestos Horizon. A serious defect of Peacock's hypothesis is that it does not explain why only some massive riebeckite bands should have been converted to crocidolite, whereas in others the parallel orientation of the riebeckite crystals is conspicuously absent.

Du Preez (1944, p. 291) considered it likely that the crocidolite in the Thabazimbi area was formed as a result of the metamorphism exercised by the Bushveld igneous intrusion, but did not elaborate on this theory.

Visser (1944, pp. 250 and 251) stated that there are indications in many of the larger workings that the deposits of crocidolite are genetically related to the widespread Post-Waterberg tectonic disturbances, and suggested that during this period of mountain-building, conditions favouring the crystallization of crocidolite were created.

Du Toit (1945, pp. 186 - 199) felt that simple thermal or load-metamorphism, as advocated by Hall and Peacock, was inadequate to cause asbestos to form, as, under such conditions, a far more uniform though unorientated growth would be expected. He stressed the association of crocidolite asbestos with folds, and concluded that crocidolite is essentially a stress-mineral formed by the recrystallization of massive unorientated riebeckite (Hall's "potential" or "mass-fibre crocidolite") as a result of dynamic metamorphism of the banded ironstone during crustal deformation in Post-Waterberg time. He attributed the orientation of the fibre normal to the bedding to the regional compression which mostly happened to be directed horizontally, i.e. about parallel to the bedding, and assumed that fibrous growth would take place in the direction of least stress.

The objection against Peacock's hypothesis cited above, viz. why only some bands of massive riebeckite have recrystallized to crocidolite, is equally valid in the case of Du Toit's hypothesis. If the metamorphism as a result of directed pressure during Post-Waterberg deformation was strong enough to cause the recrystallization of riebeckite to crocidolite, it would be logical also to expect recrystallization of the minerals which have a micaceous habit, eg. minnesotaite and stilpnomelane, so that the plates would lie in a plane normal to the direction of greatest pressure. These minerals generally show no preferred orientation.
Assuming crocidolite to be a stress-mineral, its direction of growth must have been limited in all directions except in the direction of the c-axis. In the case of directed pressure, such as that proposed by Du Toit, crystal growth is limited in one direction only. In the amphiboles the unit cell dimensions are nearly twice as long in the direction of the b-axis as in the direction of the a-axis. Assuming then that, for some reason or another, the crystals become orientated with their c-axes parallel, it would appear logical to expect that under directed pressure the crystals would also grow with their a- and b-axes parallel to one another. In other words, orientated, tabular crystals would be expected. All recent investigations by means of X-rays (eg. Garrod and Rann, 1952; and

Vermaas, 1952) have confirmed that in fibres of amphibole asbestos the c-axes are parallel, but otherwise there is no preferred orientation.

Visser (1944, p. 251) mentioned that in the Blackridge mine asbestos of longest fibre and best quality seems to be confined to the crests of the small anticlines and overfolds, and stated that the direction of growth of the fibre is parallel to the axial planes of the folds. According to Du Toit (1945, p. 203), the arches and troughs of folds are frequently attended by fibre-swellings, although these are not always situated axially. Both Visser (idem) and Du Toit (p. 197) saw a causal connection between the Post-Waterberg folding, with the associated stress-conditions, and the origin of the crocidolite. The present writer has seen numerous exposures of reefs of asbestos in which the quantity of fibre increases in the crests and troughs of folds as observed by Visser and Du Toit, but has also found that in many folds there is a marked decrease in the quantity of fibre present not only along the flanks of the folds but also in their crests and troughs. This phenomenon is clearly illustrated in the Pomfret Asbestos Mine, and at the Koegas Asbestos Mine there is no obvious relation between the development of asbestos and the major tectonic features, eg. the famous Westerberg Syncline. Similar examples may be cited from all parts of the Cape asbestos belt, and the observations are confirmed by Wasserstein (1938, p. 63), who states:

> "The beds of the asbestos zone are often folded, contorted and faulted. It is noteworthy that the richer workings of the Eastern Range have a good development in this folded structure and that the number of seams and fibre-length increase in the arches of the folds. It is, however, difficult to link this folding with the genesis of asbestos, for crocidolite occurs also in undisturbed beds and the distribution of folded structure with the better development of asbestos does not necessarily hold for the whole crocidolite belt".

Possibly the most striking development of amphibole asbestos in unfolded rock is at Penge in the Transvaal, where fibres of amosite attain lengths of up to 12 inches, yet the rock dips constantly at about 17 degrees without any folding. On the other hand the amosite developed in the intensely folded Malips River area is relatively short.

That there is a greater development of fibre in some folds cannot be denied, but that the fibrous habit of amphibole asbestos is directly related to folding is therefore not in accord with all the observed field-relationships.

It has been shown on page 114 that the effect of dynamic metamorphism on the banded ironstone is relatively small. In the Lake Superior region James (1955, pp. 1455 and 1461) found that the metamorphism was not synchronous with deformation. Metamorphism and deformation are independent variables in the orogenic scheme for that particular region. In the Cape Province relief of pressure during the periods of Pre-Loskop and Post-Waterberg deformation took place by folding rather than by faulting. Only in areas of maximum deformation was relief of pressure attained by thrust-faulting. The ease with which folding took place raises doubts as to whether sufficient stress ever existed in the rocks to form stress-minerals (assuming that such minerals do exist.)

In all the previous mineralogical descriptions of crocidolite the association of magnetite with the seams of crocidolite is mentioned. In the literally thousands of specimens of crocidolite examined by the writer, this association of magnetite and crocidolite was invariably seen, and not a single specimen of crocidolite could be found where one or both sides of the seam were not bounded by a layer of magnetite.

Du Toit (1945, p. 193) stated that the material from which crocidolite was formed must have had an excess of iron oxide over that needed for its conversion to crocidolite, and that the excess was expelled by the growing crystals in the form of a magnetite "screen" which was constantly pushed out ahead of the crystals. He stated further (p. 194) that the magnetite "screen", developed ahead of the growing fibre, takes its shape and thickness from the fibre. In the thousands of specimens examined by the writer, he could find no relationship between the thickness of the seams of asbestos and of the associated bands of magnetite. Furthermore, single bands of magnetite lying adjacent to seams of crocidolite persist without any change in thickness even after the crocidolite peters out. This is clearly illustrated in Plate X. Du Toit's contention that these bands of magnetite were formed as a result of the crystallization of the crocidolite, cannot therefore be accepted.

On the other hand, there is evidence to show that some excess material was expelled by growing crystals of amphibole asbestos. A good example of this phenomenon is illustrated on Plate X (b). In this specimen the material expelled consists of small crystals of magnetite scattered through a ground-mass of pale green material identical in appearance with the adjacent prieskaite, except that the small green laths are orientated at random in a manner similar to the crystals of riebeckite in the massive blue bands. The difference in appearance between the expelled material and the bands of magnetite is clearly visible. It can also be seen that the thickness of the layer of material expelled is related to the thickness of the seams of asbestos.

It has been shown on pages 38 and 106 that at least some of the crystals and layers of magnetite pre-date the crystals of amphibole, and on pages 108 to 114 that the total effect of regional metamorphism was so small that no new minerals could have been formed in the banded ironstone of the Lower Griquatown Stage during regional metamorphism. Consequently, one is forced to the conclusion that all the crystals of magnetite were formed at approximately the same time, whether in layers consisting almost entirely of magnetite or in the form of isolated crystals lying in layers consisting of other minerals, eg. chert, and that this also holds for all the crystals of amphibole which were formed subsequently either in the form of asbestos or in the form of laths and needles orientated at random. There appears to be no reason why more than one generation of either of these minerals should have formed, except locally where the temperature of the banded ironstone had been increased abnormally by the intrusion of igneous material, as described on pages 114 to 117 . Indeed, it would be difficult, if not impossible, to suggest any agency or process as a result of which more than one generation of either of these minerals could have been formed in the banded ironstone.

It has been shown on pages 38 and 106 that where the parent-material of the amphibole was in contact with crystals of magnetite, needles of amphibole grew preferentially from an initiating surface of magnetite. Where crystals of magnetite were dispersed in a layer with but little parent-material of amphibole, the amphibole crystallites grew from the magnetite crystals in radiating clusters (Plate VIII (a)). Where the magnetite crystals were arranged in bands, the amphibole crystallites grew more or less perpendicularly from such magnetite bands (Plates VIII (b) and (c)). In layers free from magnetite, there were no centres of crystallization and therefore no control over the orientation of the amphibole crystals, and the mineral crystallized without any preferential orientation to form either disseminated needles or laths orientated at random in layers of silica or silicate, or else layers consisting almost entirely of unorientated laths of riebeckite (the so-called "mass-fibre" or "potential crocidolite" layers), depending on the quantity of parent-material of amphibole available in the different layers.

It is clear, therefore, that the magnetite played a most important role in the orientation of the amphibole crystallites. If one were now to postulate a layer consisting essentially of parent-material of amphibole lying in contact with a band of magnetite, it may be assumed that, as in the examples cited above, amphibole crystallites would have/ started to grow from the magnetite layer, and approximately normal thereto. As crystallization proceeded, interference would have taken place between those crystals that were out of line. It is possible that solution may have taken place at those points where normal growth was impeded and this material was again precipitated at points where unrestricted growth was taking place. Consequently, as growth proceeded, the imperfect original alignment was improved constantly so that, after all the parent-material of amphibole had crystallized, the amphibole needles were orientated perfectly parallel to one another to form a seam of cross-fibre asbestos.

According to the above hypothesis, therefore, amphibole asbestos is considered to have crystallized as such directly from a parent-material of amphibole, and not by recrystallization of bands of massive riebeckite as previously generally accepted.

A marked increase in temperature is not essential. In fact, should the temperature exceed a certain degree, crystallization would be accelerated and the riebeckite crystals would be orientated at random. The effects of intrusive sills on the crystallization of crocidolite have been described on pages 114 to 116. Furthermore, it is clear that asbestos fibres are formed not because of, but in spite of the increased pressure developed as a result of the burial of the parent-material. The only effect of this pressure is to aid in the dehydration of the material. The very gentle, fine waves observed in the direction of the length of the fibres of some crocidolite seams could also have originated as the result of continued downward pressure due to the weight of the superincumbent strata. The finely undulating appearance of the crocidolite is retained in its quartz pseudomorph, "tiger's eye", and gives rise to the highly-prized chatoyance of this semi-precious stone, which is (incorrectly) referred to by jewellers as "crocidolite".

The crystallization of amphibole asbestos from an initiating surface of magnetite and normal thereto is in accordance with the observed behaviour of other minerals which have crystallized from gels rather than solutions. Peacock (1928, p. 279) cites the examples of goethite, serpentine and chalcedony, which commonly develop a fibrous or platy structure in which the long axes of the crystals lie normal to the bounding surfaces of the mineral body.

Bending of the magnetite bands as a result of the growth of the asbestos is common, and easily understood. Where the growth of the fibre was obstructed in the direction away from a magnetite band, the growing crystals made room for themselves by pushing the magnetite band backwards into an adjacent layer. Unequal rates of fibre growth caused a small amount of lateral movement of material in the adjacent layer. This material then made room for itself by bulging into the growing crocidolite layer at a different point. Parent-material of amphibole was transferred from this point to the site of most rapid fibre growth. As this process continued, original inequalities in the rate of fibre growth were intensified, and the well-known "cone-" and "corrugated" structures, described by Hall (1930, pp. 78 - 84) and Du Toit (1945, pp. 181 - 182), were formed. These structures are most frequently encountered where two adjacent bands of fibre have grown simultaneously [Plate III (c)]. It is instructive to note that the upper contact of the upper seam and the lower contact of the lower seam are generally straight, but that the thin layer of material in between the seams has been highly contorted as a result of the differential rate of growth of the fibre in the two seams of asbestos. Consequently, although the length of the fibres varies rapidly in any one of the seams, the total quantity of fibre in the two seams remains constant.

Fibres of amphibole asbestos may grow from either the one or the other or from both sides of a magnetite layer, as illustrated on Plate X. Fibre growing from both sides of a single layer of magnetite is fairly rare. An example of this type of growth is illustrated on Plate X (b) (centre, left). Where there was a rapid alternation of bands consisting of nearly pure magnetite and parent-material of amphibole, it is not unusual to find that fibres of asbestos had grown between many of the magnetite bands. Sometimes the layers of magnetite become ruptured when rapid fibre growth takes place, and a small quantity of material may then be transferred from one layer to another as soon as the opening in the magnetite band is large enough for material to be pushed through. Inequalities in the rate of fibre growth become even more intensified, as illustrated on Plates X (b) and (c).

J. H. Genis (personal communication) agrees with the present writer's conclusion that the fibres grew from pre-existing layers of ferruginous material (which could have been either magnetite or a parent-material of magnetite) but, to conform with the experimental work by Taber (1916, 1917, 1924, 1926) on the origin of asbestiform minerals, Genis suggested that the crystals originally started growing from the side of the ferruginous material opposite to that on which the parent-material lay, and that the parent-material of amphibole moved through the band of ferruginous material by capillary action. As crystallization of the fibre proceeded, the band of ferruginous material was pushed backwards into the parent-material of amphibole. Thus the growing crystals would be fed only from the direction of the layer of ferruginous material, and this would result in perfectly parallel orientation of the fibres. It may be noted that, according to this hypothesis, every magnetite band associated with a fibre band should now lie on the side of the present fibre band opposite to that side on which it lay before the fibre started crystallizing. The material which the present writer considers to be unsuitable material expelled during fibre growth is considered by Genis to be the remains of the parent-material which did not pass through the "screen" of ferruginous material. It should be pointed out that, unless the size of the particles of the ferruginous material precipitated was of the same order as the average diameter of a single asbestos fibre, Genis's hypothesis has no advantage to offer over the assumption that asbestos fibres crystallized from an initiating surface of magnetite into the parent material. From the electron-photomicrograph illustrated by Vermaas (1952, Plate XXXV, Fig. 1) it is clear that the average diameter of crocidolite is certainly smaller than one tenth of a micron, possibly very much smaller.

Genis' theory appears to offer a simple explanation of the perfectly fibrous habit of amphibole asbestos. However, some of the observed relationships between the magnetite bands and the fibre bands are difficult to reconcile with this theory. If all the magnetite bands associated with the fibre could be returned to the opposite sides of the present fibre bands, i.e. to the position where (according to this hypothesis) they were originally deposited before the growth of the asbestos took place, they would often lie in abnormally irregular planes in an otherwise regularly-banded rock. Although this difficulty could be overcome to a certain extent by assuming lateral movement of material in the various bands, it is difficult to visualize the formation of the structures illustrated in Plate X by this process. The formation of two asbestos seams, one on either side of a magnetite band, as illustrated in Plate III (c), is rather difficult to explain. Genis suggests that the magnetite band now separating the two asbestos seams, originally consisted of two layers of ferruginous material, one lying on either side of a single layer of parent-material of amphibole. As fibrous growth proceeded, the two layers of ferruginous material were pushed into the parent-material as a result of fibrous growth on the outsides of the two bands of ferruginous material, until eventually the latter bands came together in between the two seams of fibre. Although this reasoning could offer a satisfactory explanation for the relationships observed in some specimens, it is manifestly impossible to explain the development of fibre on both sides of the magnetite band illustrated in Plate X (b) by this hypothesis. In this specific example there can be no doubt that the magnetite band did not originate by the amalgamation of two original bands of ferruginous material.

To summarize: No theory has yet been advanced which explains satisfactorily the observed mode of occurrence of amphibole asbestos. The mode of origin of all types of amphibole asbestos now found in typical cross-fibre seams interstratified with the banded ironstone of the Lower Griquatown Stage, is identical. The writer suggests that this amphibole asbestos was formed not by recrystallization of the massive counterpart of the asbestos, but by crystallization of primary parent-material of amphibole. The fibrous habit of the asbestos was caused by crystallization of the amphibole perpendicular to an initiating surface of pre-existing magnetite. Where no magnetite was present, there was no control over the orientation of crystals formed from the parent-material, and layers consisting of intimately intergrown, unorientated crystals of amphibole were formed. All observed macro- and microstructures associated with amphibole asbestos can be explained satisfactorily by this hypothesis.

3. THE FORMATION OF ECONOMIC DEPOSITS OF AMPHIBOLE ASBESTOS.

The study of the origin of amphibole asbestos would be but of academic interest were it not for the fact that in certain areas the concentration of the asbestos is high enough to warrant extraction. A comparative study of the mode of occurrence of the asbestos in the crocidolite mines of the Cape Province revealed that in many of them the deposits have certain geological characteristics in common, and that from these characteristics certain conclusions may be drawn regarding the factors that controlled the formation of economic deposits of the asbestos. Characteristic features of the various deposits will be discussed separately, and an explanation sought for each.

A feature of the asbestos seams present near the base of the Lower Griquatown Stage is their rapid thickening and thinning in the plane of the bedding. This pinching and swelling is not restricted to the asbestos seams only, but it is also present in the banded ironstone, and is therefore at least in part of primary origin. The origin of these irregularities in the banding of the ironstone has been discussed on page 100, and the same explanation applies also to the seams of fibre. These irregularities in the thickness of asbestos seams would be further accentuated by differential rates of growth of the fibre during crystallization, as indicated on page 128. It is instructive to note that, in the Koegas-Prieska area, the Intermediate and Westerberg Asbestos Horizons are well known for their amazing consistency. In these Horizons the asbestos is found in banded ironstone with remarkably regular bedding-planes.

In some areas economic concentrations of asbestos are found in banded ironstone in which no folding is noticeable, for example in the vicinity of Klein Naauwte, Buisvlei and Geduld in the Prieska area, and in many highly folded areas there is no regional correlation between the folding and the distribution of the asbestos, eg. in the workings on the farm Asbestos Reefs, 12 miles south of Prieska. Superimposed zones of greater development of fibre are generally absent in these areas and one reef in a horizon may contain little asbestos at a certain point, whereas other reefs above and below it may contain many bands of fibre. It appears obvious that in these deposits the presence of asbestos in greater quantities than usual is a primary feature: A greater number of thicker bands of parent-material of amphibole had been precipitated at the time of deposition of the Lower Griquatown Stage. These deposits of asbestos are the most difficult to locate unless they have already been exposed on surface by erosion.

The fact that greater concentrations of asbestos are frequently associated with folds was already known early in this century by prospectors, and especially by the Coloured contractors, who invariably searched for asbestos in areas where folding was visible. In many of the more extensively developed mines, especially north of Griquatown, eg. the Hurley and Bretby mines, greater development of asbestos in the larger, open folds is obvious.

Asbestos seams are more numerous and thicker towards the crests of anticlines or the troughs of synclines. Various reefs are frequently better developed in zones superimposed upon one another, giving rise to the "saddle-reefs" described by Du Toit (1945, p. 191). The writer has also observed that where seams of fibre are followed away from the zone of maximum development towards the edges of any deposit, the individual seams of fibre become thinner until eventually they are no thicker than a pencil-line, and finally vanish altogether, and that at the same time the layers of rock above and below the seam come closer to each other until, when the seam vanishes, they are in contact with, or separated only by the band of magnetite which always lies adjacent to the seam of asbestos. The place of the seam of asbestos is not taken by a band of non-asbestiform material, except where the band of magnetite peters out at the same time as the seam of crocidolite, as for example, in some of the exposures in the Buisvlei mine described on page 45.

It is clear that the development of "saddle-reefs" over vertical distances of more than one hundred feet of banded ironstone could not have been a primary depositional feature. In areas where the rock had not been subjected to intense folding during the period of Post-Waterberg deformation, the fibre in the seams of asbestos is as a rule orientated perpendicular to the bedding-planes. The fibre shows no sign of disturbance and clearly crystallized in situ. One is therefore led to the conclusion that the reason for the greater development of longer fibre in the crests and troughs of the folds is that in these positions the bands of parent-material of amphibole were thicker than in the flanks of the folds before the asbestos crystallized. An obvious explanation for the thickening of the layers of parent-material of amphibole in the crests of anticlines or in the troughs of synclines is that during the period of mild Pre-Loskop deformation the layers of parent-material of amphibole were still in a fairly plastic state and relief of pressure in such layers was effected by lateral movement of the material. This would give rise to a series of similar folds, as defined by Billings (1954, p. 56), in which all the more plastic layers would become thinner in the limbs and thicker near the axes of the folds. Stronger or more competent beds would preserve a relatively uniform thickness.

During subsequent Post-Waterberg folding, the gentle Pre-Loskop folds have been intensified in many places, as, for example, in the workings on Leelykstaat. If some of the parent-material of amphibole was still in a plastic state during the period of intense Post-Waterberg folding, or if the crystallization of the asbestos was the result of dynamic metamorphism during this period of folding as postulated by Du Toit (1945, p. 197), then one would expect that the development of longer fibre in the crests and troughs of the folds would become even more pronounced. At first sight this may often appear to be the case, as for example, in the specimen illustrated in Plate III (b). However, on closer examination it will be seen that the marked increase in the thickness of the asbestos seams does not materially affect the true length of the fibres of the asbestos seam. Although the thickness of the asbestos seam in the flanks of the folds decreases, the actual length of the individual fibres does not appear to have been affected by the Post-Waterberg folding. The fact that the seam appears thinner in the flanks of the fold is due to the fact that in the flanks of the folds the fibre is no longer perpendicular to the bedding-planes, but is inclined thereto. The direction of the inclination of the fibres is opposite in the flanks on either side of the crests or the troughs of the folds. It would appear, therefore, that the seams of asbestos had become stretched during the period of Post-Waterberg folding, but that the total quantity of fibre developed remain unchanged, regardless of the intensity of folding. The above-mentioned facts indicate that the amphibole asbestos crystallized after the period of mild Pre-Loskop folding, but before the intensive Post-Waterberg deformation took place. It is therefore concluded that the total quantity of fibre developed in the banded ironstone was not increased during the period of Post-Waterberg folding. This explains why the early prospectors did not find larger quantities of asbestos in many of the folds in regions that had been subjected to Post-Waterberg folding, and also explains Wasserstein's observation (quoted on page 123) that the better development of asbestos associated with well-developed folds does not necessarily hold for the entire crocidolite belt. In areas where greater quantities of asbestos had been formed as a result of Pre-Loskop folding, and which had subsequently been subjected to Post-Waterberg folding, but where the axes of the two sets of folds do not coincide, there may be no obvious connection between the folding and the distribution of the asbestos, as, for example, in the workings on Stilverlaat, 10 miles north of Koegas. It then becomes necessary to determine the positions of the Pre-Loskop folds by meticulous large-scale mapping.

In some mines, eg. the Pomfret Asbestos Mine, there is a noticeable decrease in the development of asbestos in all tightly folded areas. Although small lenses of long fibre are developed in the crests of some of the folds, the total quantity of fibre present in the tight folds is very much less than the total quantity of fibre present in the same reef a small distance away from the folds. It is concluded that most of the parent-material of amphibole was squeezed out of the limbs of the tight folds during folding that took place prior to the crystallization of the asbestos.

As a result, the layers of parent-material of amphibole became thinner in the zones of greatest stress and the quantity of asbestos formed in these zones is less than in areas where the stress had not been so great.

In many mines, eg. the Koegas Asbestos Mine, there is a decrease in the thickness of asbestos seams as some faults (now generally occupied by dykes) are approached. That the dykes were intruded after the crystallization of the asbestos may be inferred directly from the recrystallization of the asbestos fibres to tabular riebeckite crystals adjacent to the dykes. The most likely place for faulting would be along pre-existing zones of weakness in the banded ironstone, and these zones were probably formed in areas where stress had been greatest. It has been shown in the previous paragraph that the quantity of asbestos formed in these areas is less than in areas where the stress had not been so great. Faults developed along the zone of weakness, probably at a later stage of the rock's history when relief of pressure could no longer be obtained by plastic flow of material along the layers. Dykes subsequently intruded along the faults, and the asbestos seams adjacent to the dykes were "burnt" as a result of the increase in temperature of the rock close to the contact with the dyke.

To summarize: Some economic deposits of amphibole asbestos have been formed independently of structural control, but many have been formed as a result of local thickening of the layers of parent-material of amphibole during the period of gentle Pre-Loskop folding. In areas of maximum stress during this period of folding, parent-material of amphibole was squeezed out of the tight folds and the total quantity of asbestos developed in them is less than in adjacent, less disturbed areas. The crystallization of the asbestos took place between the period of mild Pre-Loskop folding and the period of intense Post-Waterberg deformation. In some areas Pre-Loskop folds were accentuated during the Post-Waterberg orogeny, but in other areas traces of the gentle Pre-Loskop folds were practically obliterated by strong Post-Waterberg folding.

4. The Persistence of Economic Deposits of Amphibole Asbestos with Increasing Depth.

A review of the literature on amphibole asbestos reveals a universally pessimistic outlook concerning the persistence of economic asbestos deposits with increasing depth. Hall (1930, pp. 72, 75 and 262) stated that fibre was not found to persist in economic quantities below a vertical depth of approximately 200 feet in the Westerberg Mine, and also mentioned various other deposits wherein the asbestos appeared to peter out roughly where the Fresh Zone had been intersected in underground workings. He reached the conclusion (p. 262) that "in considering the question of persistence in depth, it may eventually be found that some connection between fibre display and the present surface has to be taken into account", and tentatively suggested (p. 263) that the latest step in the transformation of the layers of massive amphibole into cross-fibre seams may not depend on deep-seated conditions at all, but upon factors within the zone of weathering.

Du Toit (1945, pp. 199 - 201) concluded that amphibole asbestos should persist in depth, but that its most valuable property, namely its fibrous habit, may be largely a secondary and fairly recent property developed under weathering of a prismatic amphibole in which a microscopically fibrous structure had up to then been latent. In other words, economic deposits of amphibole asbestos should be expected only in the Weathered Zone.

By means of underground development deeper into the Fresh Zone, it has now been established that the quality of crocidolite, amosite and prieskaite does not deteriorate with depth. In fact there is a marked improvement in all the physical properties of asbestos that has been extracted from the Fresh Zone. From specimens recently obtained from bore-holes drilled by diamond-drill, it has now also been confirmed that the excellent quality of the amphibole asbestos in the Fresh Zone persists to depths appreciably greater than one thousand feet vertically below the base of the Weathered Zone. It has also been confirmed that the quantity of asbestos developed in the various reefs of the Westerberg Asbestos Horizon in the Fresh Zone is comparable with the quantity of fibre developed near surface. In some places, intersections in deep bore-holes have even indicated a progressive increase in the fibre content of some reefs with depth. These observations are in accordance with the writer's hypothesis regarding the origin of amphibole asbestos, namely that asbestos fibre was formed by direct crystallization, and not as a result of recrystallization of massive amphibole under conditions of stress, weathering, or any other influence from outside. It follows then, that economical deposits of amphibole asbestos may be expected at any depth below surface.

The lenticular habit of the economic deposits of amphibole asbestos has been described on pp. 132 to 138 . It follows that all these deposits must have definite boundaries, both along the strike and at right angles thereto, beyond which they wedge out. Furthermore, as all the deposits described in previous literature were originally exposed on surface by erosion, it also follows that a portion has already been removed and that they must eventually become uneconomical when followed along the strike and at right angles thereto. It is from observations made on deposits of this type that the fallacy arose that the deposits of amphibole asbestos are restricted to fairly shallow depths. It may be added that in all the mines described by Hall in which the asbestos supposedly petered out near the Fresh Zone, and in which underground development has since been extended to deeper levels, further economic deposits of asbestos have been discovered, and in many mines the extraction of asbestos is now confined almost entirely to the Fresh Zone.

The realization of the fact that economic deposits of asbestos may be found at depth, even though there is no indication of asbestos on surface, and that the quality of the asbestos from deeper workings in the Fresh Zone is superior to that of asbestos found near the surface, has influenced the prospecting policy greatly in recent years. In the past, prospecting operations were carried out exclusively to determine the extension of deposits of asbestos exposed on surface, whereas now the accent is on exploration for new deposits at favourable depths so that the entire deposit of unweathered asbestos is available for extraction. Before 1954 diamond-drilling through banded ironstone had been considered impossible, or at best unreliable and uneconomical. However, through constant research new drilling-techniques have been developed during the past six years so that diamond-drilling, both from surface and underground and at any angle is now common practice. Exploration by drilling has been proved economical, and nearly complete core recovery is by no means rare. In the Koegas-Westerberg mining-area alone, over 10,000 feet per year of diamond-drilling was carried out from the surface for several years to confirm the extension of asbestos at depth. The deepest hole in this area was over 3,000 feet.

The first completely hidden deposit of asbestos to be discovered by modern prospecting methods is that now known as the Number Two Mine at Pomfret. The first intersections of fibre at this deposit were made during the latter half of 1954, after a cover of up to 90 feet of Kalahari sand had been penetrated in some boreholes. Further systematic drilling confirmed the presence of an extensive, rich deposit of crocidolite. In addition, reasonably accurate underground contours could be drawn of the various reefs on the horizon; information which proved of appreciable value for the future lay-out of the mine. Subsequent development underground has shown that the Number Two Mine at Pomfret is probably the richest consistent deposit of crocidolite ever found in the North-western Cape, even though it is not as extensive as the unique Koegas-Westerberg deposit. Since then, other deposits have been discovered by the same methods, so that there is now no longer any doubt as to the persistence of amphibole asbestos at depth. This knowledge, combined with the development of suitable, modern exploration techniques, which are constantly being improved, assures the asbestos industry of an adequate supply of raw material for the forseeable future.

B. PROPERTIES AND USES OF AMPHIBOLE ASBESTOS.

1. Crocidolite.

a. Physical Properties.

The outstanding physical characteristic of crocidolite is its fibrous structure. The most striking difference between asbestos and natural fibres of animal or vegetable origin is its non-flammability. Furthermore, each filament of animal or vegetable fibres is of measurable and fairly constant diameter and is indivisible into finer filaments, whereas fibres of asbestos can be subdivided to a degree that is limited only by the process employed. The ultimate size of a single fibre has not yet been determined, but, as stated on page 130 , it is probably appreciably less than one tenth of a micron.

Crocidolite from some deposits or reefs is more easily fiberized in the mill than crocidolite from other deposits or reefs, even when given the same treatment. A specimen of crocidolite that is more difficult to fiberize therefore requires more intense milling, and it is possible that, during this process, some of the fibres may be broken into undesirably short lengths. As both the length and the diameter of the fibre are important in manufacturing processes, the ease or difficulty of fiberization of the asbestos is an important physical property.

It has been mentioned on page 123 that the individual fibres or bundles of fibre in a seam of crocidolite are orientated at random around their c-axes, so that under the microscope only an aggregate structure is visible. This fact, combined with the strong pleochroism and weak birefringence of the mineral, makes accurate determination of the optical properties of crocidolite impossible. The refractive index of crocidolite parallel to the c-axes of the fibres is approximately 1.70. As a rule the fibres are length-fast, but occasional bundles appear length-slow. Pleochroism is strong; the fibres are indigo-blue when parallel to the direction of vibration of the polariser, and a delicate lilac colour when perpendicular thereto.

Crocidolite has the highest tensile strength of all asbestos fibres. From the values given in Tables VII to X, it can be seen that there is a considerable variation in the mean and maximum tensile strengths measured on different samples of fibre, and that there is no relation between the values for the tensile strength and the chemical composition of the samples. Zukowski and Gaze (1959) have shown, by means of photographs taken at high speeds, that, during measurements of tensile strength, fibre failure usually begins at a flaw on the surface but that the stress is relieved by rupture of the relatively weak bonds between the fibres, thus producing broken fibres at that point, but exposing the surface of fresh fibres which may begin to fail at quite a different place.

Crocidolite has a higher degree of elasticity than chrysotile. The fibres are fairly flexible and suitable for spinning. Fibres of crocidolite are also harsher than those of chrysotile, so that when a small quantity of crocidolite is added to a chrysotile asbestos-cement mix, the rate of filtration is increased in the manufacturing process without loss of strength of the finished product. The asbestos-cement industry absorbs the bulk of all crocidolite produced.

Crocidolite has good electrical insulating properties. In contrast with chrysotile, the high content of iron in crocidolite does not affect its use for this purpose. This apparent contradiction may be explained by the fact that the iron is present in milled crocidolite as a silicate, whereas in chrysotile it commonly appears as impurities of iron oxide.

The heat resistance of asbestos is important in many applications, but non-flammability is sometimes confused with refractoriness. Although unburnable, asbestos decomposes and loses its essential physical properties at moderate temperatures. At $400^{\circ}C$ there is a notable deterioration in the quality of chrysotile, which decomposes completely above $550^{\circ}C$. Amphibole asbestos will withstand somewhat higher temperatures than chrysotile, but crocidolite fuses to a black, magnetic mass at about $950^{\circ}C$.

Asbestos does not have a low heat conductivity. (Bowles, 1955, p. 7). Its value for heat insulation is due to its non-flammability and also to its fibrous structure, which makes it suitable for the manufacture of laggings or boards which do not conduct heat easily because of their porous nature.

There is an appreciable variation in the values for the specific gravity of crocidolite quoted in the literature. Dana (1932, p. 578) gives a figure of 3.2 to 3.3, and Du Toit (1945, p. 169) a figure of 3.12 to 3.27. Vermaas (1952, p. 223) determined the specific gravity of crocidolite as 3.42 (± 0.01) by the immersion method using a chemical balance and also with the aid of a Walker Balance. He reported having considerable difficulty in eliminating air bubbles, which probably explains the low values given by Dana and Du Toit. Vermaas (1952, p. 224) also calculated the theoretical value for a mineral with the composition of $Na_2 (Fe''_{2.5}\ Mg_{0.5})\ Fe'''_2\ Si_8O_{22}\ (OH)_2$ as 3.43.

b. Chemical Properties.

The unit cell dimensions and chemical composition of crocidolite are the same as those of the monoclinic amphibole riebeckite, and this indicates that crocidolite is identical in structure and composition with riebeckite; only the habit is different.

Of all the types of asbestos, crocidolite has the greatest resistance to acids and alkalies, and is practically unaffected by sea-water. It is therefore used for specialized purposes where these valuable chemical properties are utilized, eg. for the manufacture of battery-boxes, filter-cloth, boiler mattresses, packings and gaskets.

The latest published analyses of South African crocidolite are those included in Hall's Memoir (1930, Tables 2 and 3). Du Toit (1945, p. 176) indicated the large variation in the values given in these analyses for SiO_2, Fe_2O_3, FeO, MgO, Na_2O, and H_2O. Various explanations have been put forward to explain these disagreements, eg. impurities in asbestos samples and replacement of Si and Na by Fe''' and Fe''.

Specimens of crocidolite from the Fresh Zone have only become available during the past ten years and even now the crocidolite bagged at most mines consists of a mixture of fibre obtained from the Weathered and Fresh Zones. As a result, all information quoted in previous literature refers to specimens that have been subjected to a certain degree of weathering owing to which the true character of the crocidolite has been masked to a greater or lesser extent. In view of the marked differences in the composition of the banded ironstone in Fresh Zone as compared with that of the rock in the Weathered Zone, the writer suspected that at least some of the disagreements in the published analyses may have been due to weathering of the fibre.

In an attempt to clarify the position, the writer selected three series of samples from the Koegas-Westerberg Mine: The first series consisted of samples taken from a single reef from surface to the deeper workings at regular intervals to investigate the effects of weathering; the second series of samples was taken along the strike of the same reef in the Fresh Zone on two levels to determine whether there is a lateral variation in the chemical composition of the same reef in the Fresh Zone; and the third series of samples was taken from a second reef in the Westerberg Horizon in the Fresh Zone, but on another farm, to determine whether there is a variation in the chemical composition of the asbestos in the Fresh Zone from reef to reef or from farm to farm. These samples were submitted to the Central Research Laboratory of the Cape Asbestos Company Limited, London, for chemical analysis and measurement of tensile strength. The results of these investigations are given in Tables VII to X.

From Tables VII and X it can be seen that crocidolite from

TABLE VII.

CHEMICAL ANALYSES OF CROCIDOLITE.

		A1	A2	A3	Mean of A4 to A7
Depth below surface (feet)		100	167	163	190 - 293
Elevation above M.S.L. (feet)		3189	3128	3072	-
SiO_2		49.40	50.85	51.40	51.26
Fe_2O_3		19.57	18.15	17.71	17.47
FeO		18.25	19.55	19.95	20.20
CaO		1.60	1.20	0.55	0.92
MgO		1.60	1.80	1.32	1.15
MnO		0.12	0.06	trace	0.06
Na_2O		6.28	6.25	6.20	6.22
K_2O		0.18	0.37	0.15	0.17
H_2O +		2.75	2.26	2.20	2.31
H_2O -		0.23	0.11	0.25	0.29
CO_2		1.00	0.08	0.20	0.22
TOTAL		100.98	100.68	99.93	100.27
Tensile Strength (lb./sq. inches)	Maximum	612,000	431,000	601,000	714,000
	Mean	366,000	256,000	325,000	306,000

Specimens of crocidolite from the Main Reef obtained from the Weathered (Leached) and Fresh Zones, Westerberg. (MW3, Plate XII).

A1 : Leached Zone. Top of 31-1 M.R. St. face on 6.11.1957.

A2 : Leached Zone, near Fresh Zone. Bottom of 31-1 M.R. St. face on 61.11.1957.

A3 : Leached Zone, Immediately above Fresh Zone. 32-1 M.R. Dr. N., peg 3317 ± 60'N.

Analysts: Central Laboratory, The Cape Asbestos Company.

Mean of A4 to A7 : from Table VIII.

TABLE VIII.

CHEMICAL ANALYSES OF CROCIDOLITE.

		A4	A5	A6	A7	Mean
Depth below Surface (feet)		190	203	256	293	
Elevation above M.S.L. (feet)		3062	3087	2974	2945	
SiO_2		51.70	51.00	51.45	50.90	51.26
Fe_2O_3		17.70	17.80	17.52	16.85	17.47
FeO		20.30	20.40	19.60	20.50	20.20
CaO		00.60	0.30	1.32	1.45	0.92
MgO		1.46	1.00	1.08	1.06	1.15
MnO		0.05	0.07	0.06	0.05	0.06
Na_2O		6.07	6.22	6.40	6.20	6.22
K_2O		0.20	0.14	0.15	0.20	0.17
H_2O+		2.18	2.51	2.19	2.37	2.31
H_2O-		0.25	0.39	0.28	0.22	0.29
CO_2		0.23	0.23	0.23	0.20	0.22
TOTAL.		100.74	99.06	100.28	100.10	100.27
Tensile Strength (lb./sq. inches)	Maximum	480,000	714,000	310,000	425,000	
	Mean	348,000	400,000	199,000	277,000	

Specimens of crocidolite from the Main Reef obtained from the Fresh Zone, Westerberg. (MW3, Plate XII).

A4 : 32-2 M.R. Dr. S., at peg 2854.
A5 : 32-1 M.R. St. Dr. N., ex 1.C.S. Boxhole (Peg 2450 + 10'N)
A6 : 33-1 M.R. St. Dr. N., ex M.R. Rse, peg 3266 + 15'N.
A7 : 33 Stn., ex No. 3 Incl., peg 1667 + 65'N.

Analysts: Central Laboratory, The Cape Asbestos Company.

TABLE IX.

CHEMICAL ANALYSES OF CROCIDOLITE.

		A8	A9	A10	A11	A12	Mean
Depth below Surface (feet)		166	186	236	236	313	
Elevation above M.S.L. (feet)		3064	3064	3064	3064	2950	
SiO_2		50.6	51.2	51.4	51.4	50.5	51.0
Fe_2O_3		17.6	17.6	17.4	17.5	16.7	17.4
FeO		19.7	20.0	19.6	20.4	19.9	19.9
CaO		1.1	1.1	0.8	0.9	1.6	1.1
MgO		2.6	2.2	2.1	1.4	2.4	2.1
Na_2O		6.3	6.3	6.3	6.3	6.1	6.3
H_2O+		2.3	2.2	2.4	2.0	2.3	2.2
CO_2		0.8	0.1	0.3	0.4	0.6	0.4
TOTAL		101.0	100.7	100.3	100.3	100.1	100.4
Tensile Strength (lb./sq. inches)	Maximum	746000	-	-	537000	403000	-
	Mean	242000	-	-	227000	248000	-

Specimens of crocidolite from the Outer Reef obtained from the Fresh Zone, Koegas (MK8, Plate XII).

A8: 81-1 O.R. Dr. S., at peg 2503.
A9: 81-2 O.R. Dr. S., peg 2710 + 60'N.
A10: 81-5 O.R. Dr. N., peg 3218 + 90'S. (Bottom Seam).
A11: 81-5 O.R. Dr. N., peg 3218 + 90'S. (Top Seam, 72" above A10).
A12: 82-4 O.R. St. Dr. S., peg 3360 + 98'S.

Analysts: Central Laboratory, The Cape Asbestos Company.

TABLE X.

CHEMICAL ANALYSES OF CROCIDOLITE.

		A13	A14	A15	A16	Mean of A15 and A16.
SiO_2		50.2	51.9	52.3	52.3	52.3
Fe_2O_3		20.5	19.4	17.5	17.1	17.3
FeO		16.6	14.6	17.2	16.5	16.9
CaO		0.8	1.1	0.7	0.6	0.7
MgO		3.1	3.7	3.7	4.6	4.2
Na_2O		5.7	5.6	5.9	5.8	5.9
H_2O+		3.1	3.7	2.7	2.6	2.7
CO_2		0.1	0.1	0.2	0.1	0.1
TOTAL		100.1	100.1	100.2	99.6	100.1
Tensile Strength (lb./sq. inches)	Maximum	549000	479000	330000	600000	
	Mean	275000	214000	150000	190000	

Specimens of crocidolite obtained from the Pomfret Asbestos Mine.

A13 : New Mine, Upper Reef, Weathered Zone.
A14 : Scale Workings, Weathered Zone.
A15 : New Mine, Upper Reef, Fresh Zone.
A16 : New Mine, Lower Reef, Fresh Zone.

Analysts: Central Laboratory, The Cape Asbestos Company.

TABLE XI.

CHEMICAL COMPOSITION AND UNIT-CELL CONTENTS OF CROCIDOLITE FROM THE MAIN REEF, WESTERBERG.

1		2		3		4	
Analysis (Mean of A4 to A7)			Atomic Proportions.	Unit-cell Contents.		Unit-cell Contents.	
SiO_2	51.26	Si	.8535	16.00		16.00	Si(16)
Fe_2O_3	17.47	Fe'''	.2188	4.10		4.10	Fe'''(4)
FeO	19.84	Fe''	.2757	5.17	6.02	5.17	Fe'', Mg(6)
CaO	0.92	Ca	.0164	0.31		0.31	
MgO	1.15	Mg	.0285	0.53		0.53	
MnO	0.06	Mn	.0008	0.01		0.01	
Na_2O	6.22	Na	.2007	3.76	3.83	3.76	Na (4)
K_2O	0.17	K	.0036	0.07		0.07	
H_2O+	2.31	H	.2564	4.81		4.00	H (4)
TOTAL	99.40	O	2.5887	48.53		48.13	O (48)
H_2O-	0.29						
$FeCO_3$	0.58						
TOTAL	100.27					plus H_2O+ (excess) 0.38%	

TABLE XII.

CHEMICAL COMPOSITION AND UNIT-CELL CONTENTS OF CROCIDOLITE FROM THE OUTER REEF, KOEGAS.

1		2		3		4	
Analysis (Mean of A8 to A12)		Atomic Proportions.		Unit-cell Contents.		Unit-cell Contents.	
SiO_2	51.0	Si	.8491	16.00		16.00	Si(16)
Fe_2O_3	17.4	Fe'''	.2179	4.11		4.11	Fe'''(4)
FeO	19.25	Fe''	.2675	5.04	6.39	5.04	Fe''Mg(6)
CaO	1.1	Ca	.0196	0.37		0.37	
MgO	2.1	Mg	.0521	0.98		0.98	
Na_2O	6.3	Na	.2032	3.83		3.83	Na(4)
H_2O+	2.2	H	.2446	4.61		4.00	H (4)
TOTAL	99.35	O	2.5898	48.80		48.13	O(48)
$FeCO_3$	1.05						
TOTAL	100.40					plus H_2O+ (excess) 0.29%	

TABLE XIII.

CHEMICAL COMPOSITION AND UNIT-CELL CONTENTS OF CROCIDOLITE FROM POMFRET ASBESTOS MINE.

1.		2.		3.		4.	
Analysis (Mean of A15 & A16)		Atomic Proportions		Unit-cell Contents		Unit-cell Contents	
SiO_2	52.3	Si	.8708	16.00		16.00	Si(16)
Fe_2O_3	17.3	Fe'''	.2167	3.98		3.98	Fe'''(4)
FeO	16.74	Fe''	.2327	4.28	6.42	4.28	9.92 Na, Fe'' Mg 6+4 (10)
CaO	0.7	Ca	.0125	0.23		0.23	
MgO	4.2	Mg	.1042	1.91		1.91	
Na_2O	5.9	Na	.1903	3.50		3.50	
H_2O+	2.7	H	.3000	5.51		4.00	H(4)
TOTAL	99.84	O	2.6624	48.92		48.16	O(48)
$FeCO_3$	0.26						
TOTAL	100.10					plus H_2O+ (excess) 0.74%	

the Weathered (Leached) Zone generally has a slightly lower content of silica than crocidolite from the Fresh Zone. There is an increase in the total content of water during weathering of the crocidolite, as well as a progressive increase in the content of ferric iron, with a concomitant decrease in the content of the ferrous iron. In other words, the process of weathering of crocidolite consists of oxidation of a portion of the ferrous iron to ferric iron, and, in the Leached Zone, a portion of the silica is removed. As a result of the leaching of the seams of fibre, the apparent specific gravity of untreated crocidolite decreases in the Leached Zone and the fibre becomes less compact and more fluffy. It is instructive to note that there is no marked decrease in the tensile strength of crocidolite which has been weathered to a moderate degree. Under extreme conditions of weathering in the Leached Zone, crocidolite alters to griqualandite, which is yellowish brown and easily rubbed down to a powder, and which contains only about 12 per cent of SiO_2 and a negligible quantity of FeO, whereas the content Fe_2O_3 is about 76 per cent, and that of H_2O about 10 per cent, (Hall, 1930, p. 38). In the Silicified Zone, both griqualandite and crocidolite are altered to tiger's eye, which consists essentially of SiO_2 (93 to 97 per cent). It is clear, therefore, that the disagreements among analyses of crocidolite published in the literature is, at least in part, the result of examination of specimens that had been weathered to a greater or lesser degree. Dr. R. Gaze (written communication) states that recent work has shown that appreciable surface-oxidation may take place during the course of preparation of samples of crocidolite for analysis. This fact may explain some of the high values for Fe_2O_3 in earlier analyses of apparently unoxidized crocidolite.

Table VIII indicates that there is little variation in the chemical composition of a specific reef of crocidolite in the Fresh Zone.

Tables VIII and IX also indicate that the composition of crocidolite does not vary much from reef to reef or from farm to farm in any one area. It is interesting to note that the analyses given in Tables VIII and IX agree reasonably well with the analysis given by Peacock (1928, p. 256) for crocidolite obtained from the Kliphuis Mine (Lower Horizon) near Prieska. Vermaas (1952, pp. 224 and 225) calculated the unit-cell contents of Peacock's specimen, and found that it corresponds closely to the empirical formula $Na_2\ Fe_2^{'''}\ (Fe^{''}\ Mg)_3\ Si_8O_{22}\ (OH)_2$, except that the water content is too high, and stated that the unit-cell contains two such units.

The writer has calculated in Tables XI and XII the contents of the unit-cell of the specimens for which the analyses are given in Tables VIII and IX. It was assumed that the CO_2 in the samples was combined with FeO in the form of an impurity (siderite). The contents of the unit-cell given in column 3 of these tables was determined by scaling the value of Si to 16. It is clear that there is a very good agreement between the theoretical and calculated contents of the unit-cell, except that, once again, the content of water is too high. In column 4 the value for H was made equal to 4, and values for O and excess H_2O+ calculated.

The consistently high values for H_2O+ shown in all analyses of asbestos is of interest. From Tables XI, XII and XIII, column 4, it will be seen that if 0.38, 0.29 and 0.74 per cent of H_2O+ is deducted from the chemical analyses of the crocidolite, i.e. if the figure for H_2O+ is reduced from 2.31, 2.2 and 2.7 per cent to 1.93, 1.91 and 1.96 per cent respectively, then the calculated unit-cell contents will all agree very closely with the theoretical values. Frankel (1953, p. 76) already found it difficult to believe that several well-known analysts should have obtained high values when the results of determinations of combined water are on the low side as a rule, and concluded that the high contents of H_2O+ in the South African crocidolites are real. Whittaker (1949, p. 316) found that the $(\frac{1}{2},0,\frac{1}{2})$ position in the unit-cell of crocidolite is unoccupied, and that this position has its nearest atomic neighbours (oxygen) at a distance of about 2.8A. He stated that there was therefore room in this position for a molecule of water, which could not enter or leave the structure as in a zeolite, but could conceivably be enclosed during crystallization under suitable conditions.

Vermaas (1952, p. 217) suggested that the excess water shown in the analyses of crocidolite may be due to a small error in the determinations of the H_2O+, and Miles (1942, p. 28) suggested that there might be some absorbed water in the thin films of talc associated with the asbestos. Frankel (1953, p. 76) felt that some of the excess water could be accounted for by Whittaker's explanation cited above, but that it is possible that small amounts of opaline silica could be present either interstitial to, or as sheaths around, the fibres. In view of the fact that excess water is so consistently reported in analyses of crocidolite, that the presence of talc or opal as impurities is not suggested by chemical and X-ray examination, and that it is theoretically possible for water, (additional to that of the hydroxyl groups) to be accommodated in the structure of crocidolite, the present writer is more inclined to accept that the excess H_2O+ reported in the analyses is present as molecules of water trapped in the crystals of crocidolite, rather than that it is derived from impurities.

The unit-cell formula for crocidolite from the Koegas Asbestos Mine, calculated from Table XI, is $Na_{3.83}$ $Ca_{0.31}$ $Fe^{''}_{5.17}$

$Mg_{0.53}\ Fe'''_{4.10}\ Si_{16}\ O_{44.13}\ (OH)_4$. For crocidolite from the Pomfret Asbestos Mine, the unit-cell formula, calculated from Table XIII, is $Na_{3.50}\ Ca_{0.23}\ Fe''_{4.28}\ Mg_{1.91}\ Fe'''_{3.98}\ Si_{16}\ O_{44.16}\ (OH)_4$.

From the unit-cell contents of the specimens of crocidolite obtained from the Westerberg Asbestos Horizon given in Tables XI and XII, it can be seen that the ratio of Fe'' to (Mg, Ca) approaches 6 to 1. Vermaas (1952, p. 225) reported a ratio of Fe'' to Mg of 5 to 1 in the unit-cell of Peacock's sample of crocidolite from the Lower Asbestos Horizon (ex Kliphuis Mine) near Prieska.

Four specimens of crocidolite from the Pomfret Asbestos Mine, 250 miles north of the Koegas Asbestos Mine, were analysed to determine the variation, if any, in the chemical composition of the crocidolite over large distances. The results of these analyses are given in Table X, and the contents of the unit-cell are calculated in Table XIII, which indicate that in crocidolite from the Pomfret region a portion of the Na has been replaced by Fe'', Ca and/or Mg, and that the ratio of Fe'' to (Mg, Ca) approaches 2 to 1.

Whittaker (1949, p. 312) calculated the following ionic formula for Bolivian crocidolite: $(Na_{1.38}K_{0.13}Ca_{0.17}Mg_{0.25})(Mg_{2.81}Fe'''_{1.66}\ Fe''_{0.48}\ Al_{0.05})\ (Si_{7.94}Al_{0.06})\ O_{22}\ (OH)_2$, from which it may be seen that the ratio of Fe'' to Mg is of the order of 1 to 6 as compared with 2 to 1 for Pomfret crocidolite and 6 to 1 for Koegas crocidolite. Bolivian crocidolite also has a lower content of sodium than Cape crocidolite.

The replacement of one element by another in varying proportions is a prevalent characteristic of all the varieties of amphibole asbestos. This variation in composition gives rise to corresponding changes in their physical and chemical properties, apart from the effect of the presence of impurities in the milled fibre. Bowles (1955, p. 3) cites the example of anthophyllite, which may give satisfactory service for some specific use when obtained from one locality, whereas anthophyllite from another deposit, although appearing to be exactly the same, may be unsatisfactory.

Few details have yet been published regarding the variations in the physical and chemical properties of crocidolite brought about by isomorphous replacement of the various elements in the molecule, but many manufacturers make comparative tests and then specify the locality, or even the mine, from which they wish to obtain fibre, eg. in the asbestos-cement industry crocidolite from the Cape Province is apparently preferred to crocidolite from Australia, which, in turn, is preferred to crocidolite from the Transvaal.

The problems of procuring suitable amphibole asbestos are therefore much more difficult and complex than those of procuring ore from which metals are extracted, because the metals, when pure, have constant properties, no matter from where they originate.

2. Prieskaite.

Peacock (1928, pp. 260 to 264) first described a greenish grey cross-fibre asbestos which is found in a manner identical to that of crocidolite on Middelwater, Keikamspoort, and Kalkfontein in the Prieska District. From a chemical analysis, combined with the optical properties of the fibre, he identified it as amosite. Kirkman (1930, p. 17) described similar fibre from Naauwte, on the bank of Orange River opposite to that on which Middelwater lies, and stated that the fibre was "of too poor a quality to be of use". Hall refers to this fibre in his Memoir

(1930, pp. 39 and 60). After an X-ray examination of Peacock's sample, Rabbitt (1948) identified it as actinolite. Frankel (1953) included a chemical analysis and a D.T.A. curve of a sample of similar fibre from Kameelfontein, which lies immediately north of Naauwte, and stated that the fibre lacks the flexibility and strength of crocidolite. In his Table 8 (p. 145) he quotes the tensile strength of actinolite asbestos as being 1,000 pounds per square inch and less.

By detailed mapping the writer has established that this greenish grey fibre is found only at a certain fixed stratigraphical position in the Prieska-Koegas area, as described on page 46 . Nowhere on any of the properties mentioned in the

TABLE XIV

CHEMICAL ANALYSES OF PRIESKAITE.

	P1	P2	P3
SiO_2	47.04	52.40	53.8
TiO_2	trace	trace	-
Al_2O_3	7.02	nil or trace	1.2
Fe_2O_3	2.43	6.37	1.9
FeO	26.10	23.11	25.3
CaO	10.84	9.30	10.2
MgO	4.96	4.73	4.3
MnO	0.15	0.12	0.4
Na_2O	trace	0.35	0.4
K_2O	trace	0.05	0.1
H_2O+	1.05	3.07	2.6
H_2O-	0.45	0.31	-
P_2O_5	trace	n.d.	-
S	0.05	n.d.	-
CO_2	0.10	n.d.	0.2
TOTAL	100.19	99.81	100.4

P1. Prieskaite.(Amosite,according to Peacock) Kalkfontein, C.P. (Peacock, 1928, p. 263, No. IV.)

P2. Prieskaite.(Actinolite, according to Frankel) Kameelfontein, C.P. (Frankel, 1953, p. 76, No. 1).

P3. Prieskaite. Westerberg, Koegas Asbestos Mine. (New analysis).

Analysts: Central Laboratory, The Cape Asbestos Company.

previous paragraph has the fibre been exposed to more than thirty feet below the outcrop, so that the specimens described by Peacock (1928) and Frankel (1953) must have been obtained from very near the surface. The present writer was able to obtain unweathered samples of the fibre from 350 feet below surface in the Westerberg Mine and from bore-hole intersections at nearly 900 feet below surface. The refractive indices of the unweathered fibre parallel and at right angles to its length are 1.683 and 1.662 respectively. The optical properties of the unweathered fibre are therefore identical to those of the weathered fibre given by Peacock (1928, p. 261) and Frankel (1953, p. 76). Specimens of the fibre from the Fresh Zone were examined in the Central Laboratory of the Cape Asbestos Company, and it was found that the tensile strength of the fibre was of the order of 165,000 pounds per square inch. A chemical analysis was carried out in order to confirm the identification of the fibre, and is given in Table XIV, No. P3.

No elaborate separation of the impurities from the fibre was carried out, and it is probable that the material analysed contained some free carbonate, quartz, and possibly iron ore. It is therefore not possible, at this stage, to calculate accurately the contents of the unit-cell. Nevertheless, some conclusions may be drawn from the analyses quoted in Table XIV, namely

(i) there is an appreciable variation in the content of aluminium in samples of fibre taken from various localities,

(ii) the content of ferric iron in the fibre is much lower than that of both amosite and crocidolite, and

(iii) there is an increase in the ratio of Fe''' to Fe'' in the fibre during weathering as in crocidolite and amosite.

In view of the marked difference in the physical properties, mode of occurrence and origin of this fibre compared with those of the amphibole actinolite and the material generally referred to as "actinolite asbestos", the writer has proposed the name "prieskaite" for this fibre. (Page 29).

V SUMMARY AND CONCLUSIONS.

1. The object of this study has been to present the characteristics of the deposits of crocidolite in the Cape Province, as well as those of the rocks with which the asbestos is associated.

2. Unweathered specimens of the rocks and the asbestos have only become available for investigation during the course of the past ten years.

3. The rock exposed above the water-table has been altered to such a degree that conclusions regarding its origin cannot be based on examination of specimens of this rock.

4. Not one of the existing theories explained satisfactorily the origin of the rock or of the associated amphibole asbestos, and the persistence of economic deposits of amphibole asbestos in depth has been open to doubt.

5. Unweathered banded ironstone consists of alternating, thin layers of pure chert, magnetite, stilpnomelane, minnesotaite, riebeckite and carbonate, and layers consisting of mixtures of these minerals in which any one mineral may predominate. Seams of crocidolite are interbedded along certain horizons in these rocks.

6. The writer has come to the conclusion that the banded ironstone was formed from material precipitated chemically in a restricted basin of deposition, in which the rate of sedimentation exceeded the rate of subsidence. The characteristic banded appearance of the rock resulted from slight variations in the pH and Eh in the basin of deposition coupled with the intermittent introduction of solutions containing predominantly either compounds of iron or of silicon.

7. The lithification of the banded ironstone was a long, continuous process which took place under slowly changing conditions, during which the mineralogical composition was reorganized continuously

in an attempt to maintain equilibrium. Movement of material during crystallization was insignificant and confined to the limits of individual layers.

8. The effects of regional metamorphism are negligible.

9. The amphibole asbestos was not formed as a result of stress set up during periods of regional folding, but crystallized directly from a colloidal precipitate of parent-material of the amphibole.

10. The fibrous varieties of amphibole developed as a result of the crystallization of minute needles of the amphibole perpendicular to an initiating surface of pre-existing magnetite. Where no magnetite was present, there was no control over the orientation of the crystals formed from the parent-material, and layers consisting of intimately intergrown, unorientated crystals of amphibole were formed.

11. The crystallization of the amphibole asbestos took place between the periods of mild Pre-Loskop and intense Post-Waterberg deformation, and the quantity of asbestos developed is often related to the gentle Pre-Loskop folding.

12. The writer feels that these views on the origin of the amphibole asbestos and the rocks of the Lower Griquatown Stage offer a satisfactory explanation for the distribution of the asbestos and its fibrous structure.

13. By means of underground development deeper into the Fresh Zone, it has now been established that the quality of the amphibole asbestos improves below the Weathered Zone, and that the quantity of fibre developed is not related to the depth below surface.

14. Several new, completely hidden deposits of crocidolite have been discovered by application of the principles outlined in this thesis.

15. This knowledge, combined with the development of suitable modern techniques of exploration, assures the asbestos industry of an adequate supply of raw material for the foreseeable future.

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The writer would like to thank the numerous persons associated with the Cape Asbestos Company, and in particular the Manager and staff of the Koegas Asbestos Mine, for their interest in the work and for assisting him in obtaining specimens and information, and in the preparation of the manuscript.

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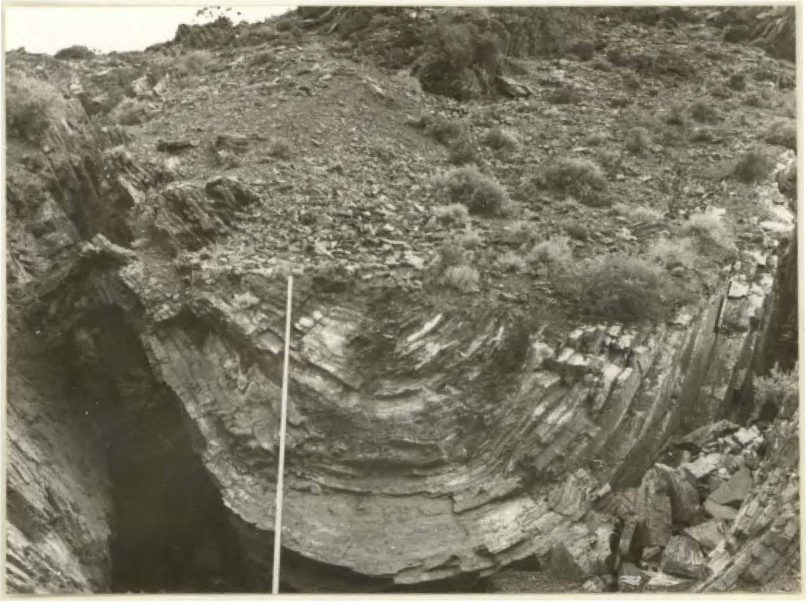
PLATE I.

(a)

(a) Banding in the rocks of the Lower Griquatown Stage.

1. Faint banding near the contact between the Lower Mudstone Beds and the Lower Shale Beds. Bore-hole W4, depth 290 feet.
2. Regular, sharp banding in finely-laminated shale with thin veins of quartz and carbonate. Westerberg Asbestos Horizon. Bore-hole W1, depth 335 feet.
3. Irregular banding in Lower Banded Ironstone Beds. Bore-hole W2, depth 2855 feet.

(b)



(b) Folded strata near Section 12 (MK12), Weilbach Valley. (The stadia-rod is 14 feet long).

PLATE II.

(a)

(a) Folding in the trough of the Weilbach Syncline, Section 11, Koegas (MK11).

(b)

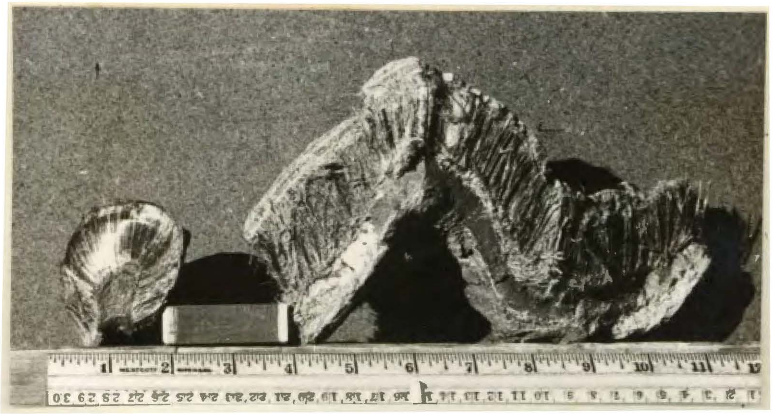
(b) Folding in the trough of the Weilbach Syncline, Section 11, Koegas (MK11).

PLATE III.

(a)

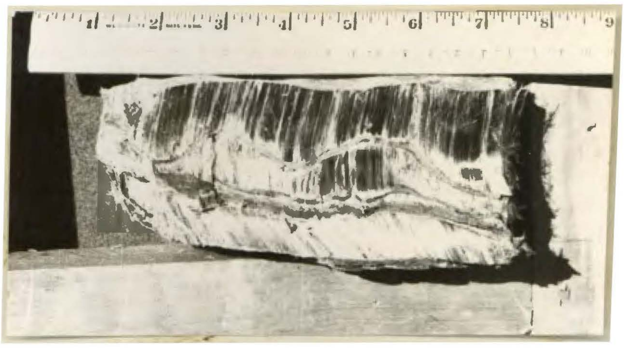
(a) "Slip-fibre" from shear-zone. Section 3, Koegas (MK3).

(b)



(b) Crocidolite in folds:

1. Malips Drift, Transvaal.
2. Leelykstaat Mine.



(c)

(d)

(c) Three seams of crocidolite. Main Reef, Section 3, Westerberg (MW3). The upper two seams are separated by a thin, contorted layer of magnetite, giving rise to "cone" or "corrugated" structures. The fibre in the bottom seam is inclined at about 50 degrees to the bedding-planes.

(d) Folded seams of crocidolite in massive riebeckite, near the trough of a minor syncline. Inner Reef, Section 8, Westerberg (MW8).

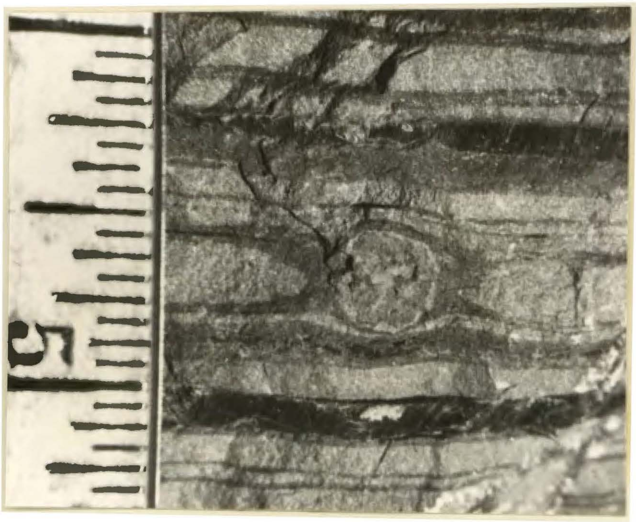
PLATE IV.

(a)

(a) General view of the Westerberg Valley behind the mill and power station, seen from north of the Orange River.

(b)

(b) Two small dykes cutting through banded ironstone. Near Section 7, Koegas. (MK7).



(c)

(c) "Blob" of riebeckite and two thin seams of crocidolite in Lower Banded Ironstone Beds, Buisvlei Mine.

PLATE V.

(a)

(a) Rhombs of carbonate (high relief) in ground-mass of minnesotaite (needles) and quartz (clear). Ordinary light, X 100. Lower Banded Ironstone Beds, Buisvlei Mine.

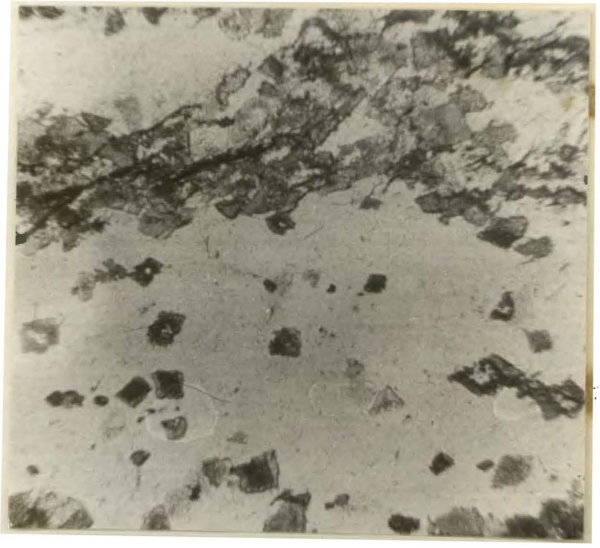
(b)

(b) Detail of (a). Ordinary light, X 500.

(c)

(c) Needles of minnesotaite and small crystals of carbonate in a matrix of microcrystalline quartz. Ordinary light, X 100. Lower Shale Beds, Westerberg.

PLATE VI.



(a)

(b)

(a) Chert band: Carbonate rhombs (high relief) in band of clear quartz. Ordinary light, X 25. Lower Banded Ironstone Beds, Westerberg.

(b) As for (a) : Crossed Nicols.

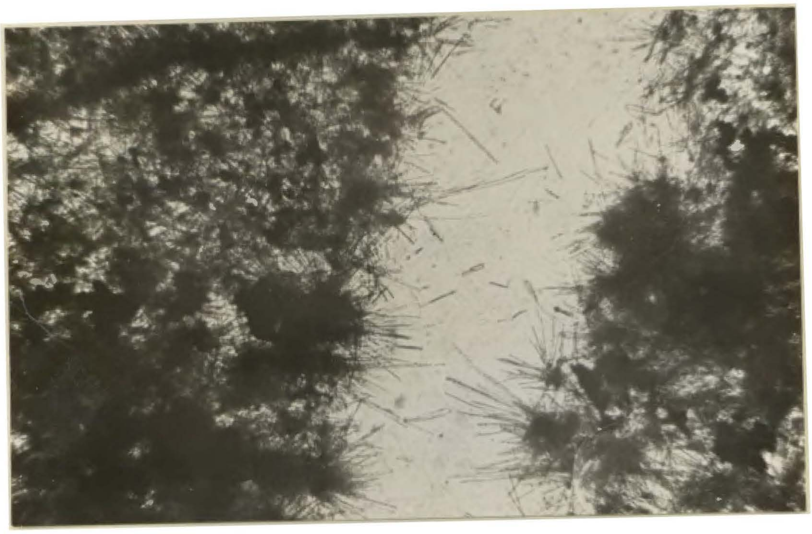
(c)

(c) Two bands: lower consists of quartz, carbonate and stilpnomelane, upper consists of quartz, magnetite and riebeckite. Note elongation of quartz grains and preferred orientation of riebeckite laths and needles in top band at an angle of 30 degrees to the bedding-plane (BB).
Ordinary light, X 25. Lower Banded Ironstone Beds, Westerberg.

PLATE VII.

(a)

(a) Vein of riebeckite (grey) cutting across layers of riebeckite and magnetite (black). Note magnetite band pushed aside by riebeckite vein. Crystals of riebeckite larger in vein than in layers. Ordinary light, X 100. Upper Banded Ironstone Beds. Westerberg.



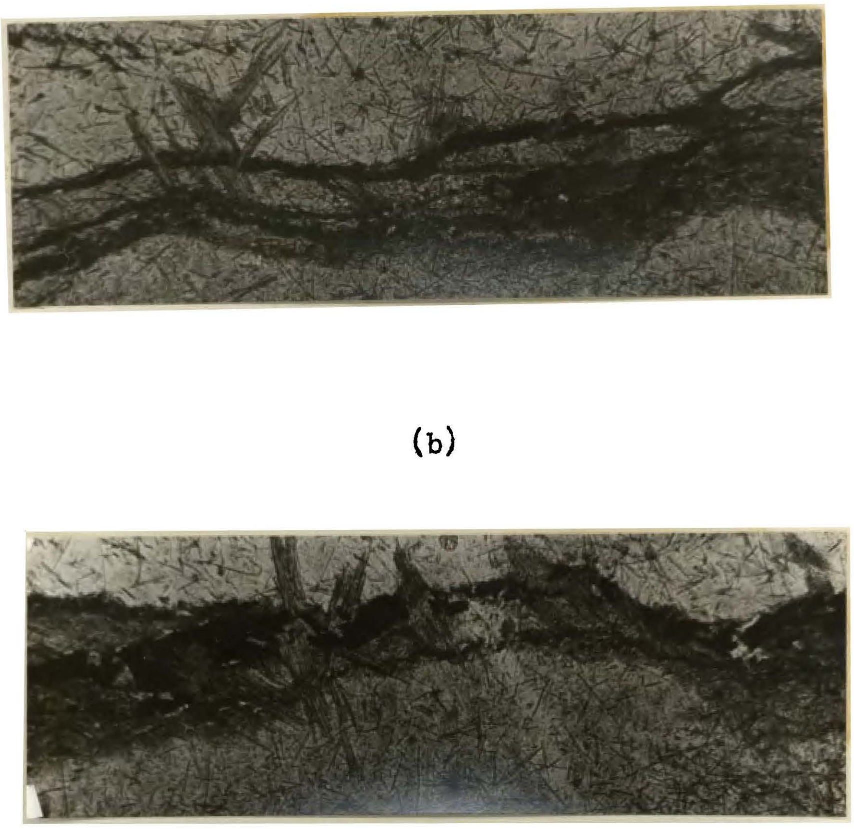
(b)

(b) Detail of vein of quartz cutting through bands magnetite and of chert, which contains small, disseminated crystals of magnetite. Note needles of riebeckite growing into quartz vein, radiating preferentially from the ends of magnetite bands bisected by the vein. Ordinary light, X 100. Upper Banded Ironstone Beds, Westerberg.

PLATE VIII.

(a)

(a) Needles of riebeckite in chert band radiating preferentially from cores of magnetite (black). Small needles in chert band are orientated at random. Ordinary light, X 100. Upper Banded Ironstone Beds, Westerberg.



(b)

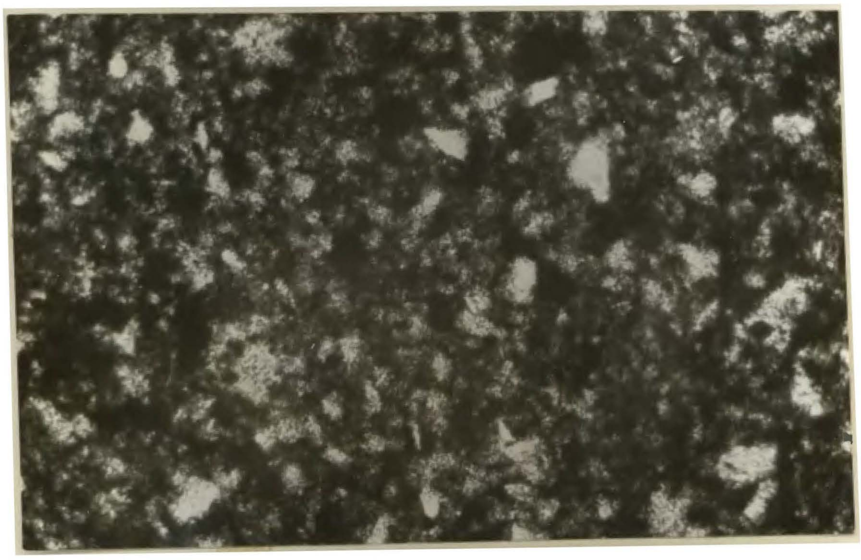
(c)

(b) and (c) Needles of riebeckite showing partial orientation perpendicular to thin bands of magnetite separating bands of chert which contain small needles of riebeckite orientated at random. Ordinary light, X 100. Upper Banded Ironstone Beds, Westerberg.

PLATE IX.

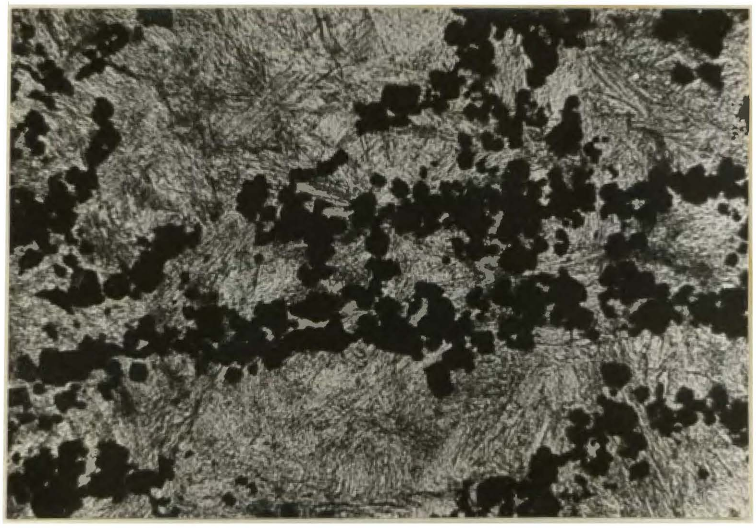
(a)

(a) Small rhombs of carbonate lying in shale consisting of alternating layers of chlorite (pale grey) and chlorite and carbonate (dark grey). Ordinary light, X 100. Lower Shale Beds, Westerberg.



(b)

(b) Angular fragments of clastic quartz (and occasional feldspar) in a ground-mass of altered chloritic material and cryptocrystalline quartz. Ordinary light, X 100. Upper Mudstone Beds, Koegas.



(c)

(c) Abnormally large flakes of minnesotaite (grey) with magnetite (black) in thermally metamorphosed rock. The original banding of the magnetite is disturbed, but is still clearly visible. Ordinary light, X 100. Westerberg Beds, Westerberg.

PLATE X.

(a)

(a) Seams of crocidolite (pale grey) and bands of magnetite (black) in wide band of massive riebeckite (medium grey, speckled). Ordinary light, X 25. Westerberg Asbestos Horizon, Westerberg.

(b)

(c)

(b) and (c) Seams of prieskaite, partly replaced by carbonate (pale grey, streaky), bands of magnetite (black), and bands of finely disseminated magnetite, carbonate and actinolite (medium grey, speckled). Ordinary light, X 25. Prieskaite Horizon, Westerberg.