THE NATURE AND ORIGIN

OF THE

CHRYSOTILE ASBESTOS DEPOSITS

IN SWAZILAND AND THE EASTERN TRANSVAAL

by

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I.   INTRODUCTION

The problem of the origin of chrysotile asbestos has
interested petrologists and mineralogists for many years.
Several excellent papers have appeared on the subject, the
most important of which are those of Keep (1929), Hall (1930),
Cooke (1937) and, more recently, that of Riordon (1955).   All
these papers, except the one by Hall, deal with deposits
occurring in massive serpentinite outside the present area -
that of Keep with the Rhodesian fields and the others with
those of Canada.

In the Eastern Transvaal chrysotile asbestos occurs both
in massive serpentinite and in serpentinized dolomite.   Over
the past six years the author has had the opportunity of
studying these deposits in detail.   Much new material has
become available since the days of Hall, and during the course
of this investigation the author has reached the conclusion
that none of the existing theories on the genesis of chrysotile
asbestos entirely explain the features observed in this area.
It is felt that the conditions under which the fibre formed in
the two types of deposits must have been essentially the same.
It is the purpose of this thesis to present the characteristics
of occurrences and to compare the two types of deposits.   It
is hoped that the conclusions drawn from the results will
throw new light on the origin of chrysotile asbestos.

The mineralogy of the serpentine minerals has also not
been cleared up entirely even though several papers have
appeared on this subject.   Over 200 specimens were examined
microscopically by the author and, of these, ten were selected

for chemical analysis and more detailed study by means of X-ray diffraction, differential thermal analysis, and the electron microscope.

II. GENERAL GEOLOGY OF THE EASTERN TRANSVAAL

The Basement Complex

Before presenting detailed descriptions of the individual occurrences investigated it is necessary to give a general survey of the geology of the Eastern Transvaal as a whole (Appendix 1).

The oldest rocks in the area form the rugged country generally known as the Barberton Mountain Land. This is built up by highly folded sedimentary and low grade metamorphic rocks which have been sub-divided into the basal Swaziland System overlain unconformably by the Moodies System (Van Eeden et al., 1956, p.44). The former can again be split up lithologically into two series: a) the Onverwacht Series, consisting mainly of highly altered basic lavas at the bottom, overlain by acid lavas, some pyroclasts and interbedded cherts; and b) the Fig Tree Series, comprised of more than 7,000 feet of sediments. In the Sheba Hills area (Van Eeden et al., 1956, p.55) the Series consists of shale and chert at the base followed by greenschists, talcose and carbonate rocks. These are overlain by shale, banded ironstone and banded chert. Graywacke and gritty graywacke follow with a few bands of chert and, on top of these, more shale with numerous bands of chert, grit and conglomeratic grit. This is followed by trachytic lava, while the top of the succession is made up of shale and graywacke.

In the southern parts of the Barberton Mountain Land the sequence has not yet been determined, mainly because of the complicated structure, poor outcrops and the absence of mining activities in rocks of this series. From the present

investigation it would appear, however, that all the rock types, except perhaps graywacke, are also represented in the south.

The younger Moodies System begins with a fairly persistent conglomerate with pebbles of chert, jasper, grit and sometimes quartz porphyry and granite, at the base. This conglomerate is overlain by calcareous and felspathic quartzite, followed by a large thickness of sandy slate, phyllite and graywacke with some interbedded quartzite.

The rocks of the several groups form a roughly triangular area stretching from Kaapsehoop in the west to near Komatipoort in the east, the southern corner lying some distance west of Mbabane in Swaziland.

The axes of the many folds are orientated more or less east-west in the northern sector of the area but swing south along the Swaziland border. The Moodies System is often infolded into rocks of the Fig Tree Series and preserved only as cappings on some of the higher ranges.

The rocks of the Swaziland and Moodies Systems were invaded first by a suite of basic and ultrabasic rocks and then by granodioritic material which Van Eeden and his collaborators termed the Jamestown Igneous Complex (Van Eeden et al., 1956, p.1) or Jamestown Plutonic Complex (p.112). They suggested that the granodioritic phase, or Kaap Valley Granite, was related to the basic phase of the Jamestown Complex in the same way as the Bushveld Granite is related to the basic rocks of the Bushveld Complex (p.1, p.127). The Jamestown basic and ultrabasic rocks have been intruded in sill-like fashion. The main rock types are green and blue serpentinite, diabase and basic schist. In the field they usually occupy a position between the Archaean granite and the rocks of the Swaziland and Moodies Systems.

The green serpentinite was considered by Hall (1930, p.114) to have been formed from a rock rich in olivine,

while the blue serpentinite was probably derived from an amphibole or pyroxene bearing rock. Van Eeden and his collaborators (1956, p.119) came to similar conclusions in that they considered the original rock types to have varied in composition from dunite, through peridotite to pyroxenite. The green variety of serpentinite was derived from the olivine rich members and the blue variety from those carrying pyroxene. As will be pointed out later, the author has found that, at least in some cases, the differences between the serpentinites are not due to differing parent rocks but have been brought about by subsequent processes.

The diabase found associated with the serpentinite occurs mainly in the Amianthus – Munnik Myburgh – Noord Kaap area and is relatively scarce in the south. Originally the rocks probably had a gabbroic composition, but they are now composed mainly of hornblende and interstitial plagioclase occasionally showing a sub-ophitic texture. In places the plagioclase is completely replaced by epidote.

The basic schists, composed mainly of chlorite and magnetite with quartz, epidote, sericite, carbonate and talc, are considered to have been derived from the basic rocks under dynamic metamorphism (Van Eeden et al., 1956, p.121). The green serpentinite has also been observed to change to talc-serpentine schist along fault-zones, while the blue serpentinite may be altered to a rock composed mainly of carbonate, amphibole or talc. In different parts of the area schists of different composition have formed from the same parent rock (Van Eeden et al., 1956, p.122).

The Kaap Valley Granite occurs as a batholithic body lying west of Barberton and south of Kaapsehoop. It has been found to be intrusive into the rocks of the Swaziland and Moodies Systems as well as into the basic rocks of the Jamestown Complex. It is a greenish-grey medium-grained rock composed mainly of plagioclase (An_6 to An_{12}), quartz,

and hornblende, with minor quantities of potash felspar and
is therefore a typical hornblende-granite (van Eeden et al.,
1956, p.124).   Willemse (1937, p.96) determined the felspar
as andesine and calls the rock a "quartz diorite", though van
Eeden and his co-authors (1956, p.125) consider the name
"granodiorite" more appropriate.   The composition thus seems
to be variable and the author has decided to retain the term
"granite" in the following discussion.

The mountainous area occupied by the rocks of the
Swaziland and Moodies Systems and those of the Jamestown
Complex is surrounded by a low lying region composed mainly
of Archaean granite and gneiss, including the Kaap Valley
Granite.   In the northern part of the area the Nelspruit
granite covers an extensive area from the Drakensberg
escarpment in the west to near Komatipoort in the east where
it disappears under the younger Karroo System.   Where best
developed the granite is composed of biotite, orthoclase and
plagioclase (An_{12} to An_{16}) (van Eeden et al., 1956, p.130).

At the contact of the granite and the basic rock
migmatization and lit-par-lit injection have often taken place.
Hornblende is then usually present in the granite.   Schlieren
of biotite as well as xenoliths of basic schist may be found
not only close to the contact but even several miles away
(van Eeden et al., 1956, p.133).   It seems then (quoting van
Eeden) that "the Nelspruit granite has not consolidated from
a normal, primary granitic magma but represents a product,
or a series of products, of a process or processes generally
known as granitization".   Read (1951, p.14) similarly
considers the Nelspruit granite to have been produced by
migmatization of semi-pelitic and more siliceous rocks.

In the area between Badplaas and Nelshoogte Pass a
granite of the Nelspruit type is also well exposed.   To the
west it disappears underneath rocks of the Transvaal System
while in the south it is overlain by Karroo sediments.

In the south-eastern portion of the area i.e. in
Swaziland, Archaean granite again adjoins the older rocks.
The composition of this granite, which is called the G.4-
granite by Hunter (1957), is similar to that of the Nelspruit
type.   According to Hunter lit-par-lit injection and
migmatization are also evident at the contact between the
granite and the basic schists.   Hunter (1957, p.110) feels,
however, that the field evidence can be interpreted in favour
of either a granitization or a magmatic origin for the granite.

After studying the structure of the Sheba Hills and
surrounding country, van Eeden (1941, pp.98-104) came to the
conclusion that the Kaap Valley Granite was solid before the
orogeny which caused the folding of the Swaziland and Moodies
rocks had taken place.   He and his colleagues (Van Eeden et
al., 1956, p.42) considered that this granite was the acid
phase of the Jamestown Complex and accordingly older than the
Nelspruit Granite.   Read (1951, p.21) differs from van Eeden
and suggests that the Kaap Valley Granite was the cause of
folding and is possibly the youngest granite in the area.

Van Eeden and his collaborators (1956, p.87) have come
to the conclusion that the Swaziland System must have been
subjected to mild folding before the deposition of the
Moodies System.   The basal conglomerate of the Moodies
System contains pebbles of a granite which has not been
observed in the field.   This has led Visser (1957, p.xxi)
to believe that this granite represented the magmatic phase
following the geosynclinal phase of the Swaziland-Kheis
cycle.   The Moodies System was then deposited in a geosyncline
which coincided more or less with that in which the Swaziland
System was formed.   The intrusion of the Jamestown Plutonic
Complex is considered by Visser to represent the first
magmatic phase of the Moodies-Gariep cycle.   Its
emplacement was followed by a period of orogenesis during
which the layered rocks were strongly folded into a series
of synclines and anticlines.   Several thrust faults

developed and where the rocks were compressed against the "hub" of the Kaap Valley Granite intense shearing took place.

During this orogenic period the older rocks must have been depressed into the deeper levels of the earth's crust where they were transformed into granitic rocks. Locally they were mobilized to such an extent that they formed true granitic magma, which rose and intruded the rocks of the Swaziland and Moodies Systems as well as the rocks of the Jamestown Complex (Visser, 1957, p.xxiii). This would represent the formation of the Nelspruit granite.

If the intense tectonic disturbance, as well as several periods of magmatic activity are considered, then the rocks of the Swaziland and Moodies Systems have undergone metamorphism of a surprisingly low grade. According to van Eeden and his fellow workers (1956, p.154) the metamorphism due to the intrusion of the rocks of the Jamestown Complex has been of a restricted nature; upon this the metamorphism associated with the Nelspruit granite has been superimposed. Yet, in spite of this, the older rocks have hardly been affected and rocks showing high grade metamorphism are only found close to the contact of the granite. Read (1951, p.14) has suggested that the rim of basic Jamestown rocks, which nearly everywhere separates the granite from the sediments, has acted as a barrier, protecting the Swaziland and Moodies rocks from metamorphism and migmatization. This view is supported by van Eeden (1956, p.154).

Post-Basement formations

After a period of erosion the first sediments of the Godwan Formation (correlated with the Dominion Reef System) were deposited on an irregular floor of Archaean granite containing xenoliths of earlier systems. These rocks, where exposed along the Drakensberg escarpment, consist of quartzite and conglomerate followed by basic lava, agglomerate

and tuff, and at the top of the succession, felspathic
quartzite and shale.

The Godwan Formation is overlain by the rocks of the
Transvaal System.   Although not originally recognised, the
two systems are in some places separated by a strong angular
unconformity.   At the base of the system the Black Reef
Series forms a weather-resistant zone composed mainly of
quartzite with some conglomerate and interbedded shaly
sandstone at or near the base.   The surface on which the
Black Reef sediments were deposited must still have been
rather irregular so that the system is often interrupted by
protrusions from the floor, (van Eeden et al., 1956, p.101).

The Black Reef Series is followed conformably by
dolomitic limestone, with interbedded shale and chert,
belonging to the Dolomite Series.   The thickness of this
series, as given by Hall (1913, p.45), varies from between
1600 and 1800 feet at Pilgrim's Rest in the north to about
120 feet east of Carolina in the south.   This thinning is
believed to be due to erosion prior to the deposition of
the beds of the Pretoria Series (van Eeden et al., 1956, p.106).

The Pretoria Series has a threefold subdivision:- at
the base the Timeball Hill Stage, followed by the Daspoort
Stage and at the top the Magaliesberg Stage.   Directly on
top of the Dolomite Series follows the Bevet's conglomerate
composed of angular chert pebbles set in a siliceous matrix.
In the southern portion of the area the rock becomes more
arenaceous and is locally known as the Rooihoogte quartzite.
The rest of the Timeball Hill Stage is built up of shales
capped by ferruginous quartzite.   The Daspoort Stage, as
well as the Magaliesberg Stage, is composed mainly of
shale with quartzite near the top of the succession.
Interbedded lava and tuff is present in both stages.

Basic sills, probably of Bushveld age, are found to
be intrusive into all the rocks of the Transvaal System.

The sills vary in thickness from only a few to several tens of feet. Although they are usually parallel to the bedding, they sometimes gradually cut across the succession.

In time the Transvaal System and the Godwan Formation are separated by the deposition of the rocks of the Witwatersrand and the Ventersdorp Systems, both of which are absent in this area except for some quartzites and conglomerates north of Pilgrim's Rest, which have been correlated with the lower Witwatersrand System and are known as the Wolkberg System (Truter, 1950, p.lvii).

After a prolonged period of erosion and intense peneplanation the youngest rocks of the area, those of the Karroo System, were deposited. The basal glacial conglomerate or Dwyka tillite is found only in the vicinity of Carolina, where it is overlain by the sandstones and shales of the Ecca Series. Along the Mozambique-Transvaal border the Karroo sediments, dipping at a low angle to the east, occur on the extension of the Natal monocline. They are here overlain by basalts and rhyolites of the Stormberg Series, also dipping eastwards.

Summarizing, the area consists of a central zone comprised of ancient rocks, mainly granite with remnants of sediments, schists, basic and ultrabasic rocks, with the Godwan Formation and the Transvaal System dipping westwards on the one side and the rocks of the Karroo System dipping eastwards on the other. Roughly speaking one can consider it as a broad anticlinal structure with a north-south axis.

Hypabyssal rocks, mainly in the form of basic dykes and ranging in age from pre-Moodies to post-Karroo, occur in great profusion throughout the area. They seem to be more abundant in the granite areas and show a pronounced orientation parallel to three directions, 30° west of north, 30° east of north and north-south. A few deviations from these directions are also found (van Eeden et al., 1956, p.137).

III.   DESCRIPTION OF THE ASBESTOS OCCURRENCES INVESTIGATED

(See Appendix 1)

LIST   OF   OCCURRENCES

A   In Serpentinite of the Jamestown Complex

1.   Havelock Asbestos Mine, Swaziland; and the M'Sauli
Asbestos Mine on the farm Diepgezet 37, Barberton district.

2.   New Amianthus, Munnik Myburgh and Sunnyside Asbestos
Mines near Kaapsehoop.

3.   The mines on the farms Stolzburg 202, Sterkspruit 239
and Doyershoek 145.

4.   Barberton Chrysotile Mine on the farm Koedoe 332, near
Malelane.

5.   Kalkkloof Asbestos Mine near Badplaas.

B   In Serpentinized Transvaal Dolomite

1.   Congo-Vaal Asbestos Mine on the farm Rietfontein 70,
portions E and F, Carolina district.

2.   Carolina Asbestos Mine on the farm Diepgezet 33,
Carolina district and the occurrence on the adjoining
farm Zilverkop 31.

3.   Badplaas Asbestos Mine on the farm Goedverwacht 32,
Carolina district.

4.   Elandshoek Asbestos Mine, on the farm Elandshoek 139,
near Montrose Falls.

5.   Occurrence of chrysotile asbestos on the farms
Olifantsgeraamte 459, Graskop 27, Normandale 280,
Kalkkloof 250, Appeldoring 60, Engelschedraai 175,
Uitkomst 183 and Rietfontein 70, portions A and B.

A   OCCURRENCES   IN   MASSIVE   SERPENTINITE

1. THE HAVELOCK AND THE M'SAULI ASBESTOS MINES

General

The Havelock Asbestos Mine is situated in Swaziland
half a mile from the Transvaal border and about one mile
due south of the trigonometrical beacon Emlembe.   It lies
12½ miles south-south-east of the town of Barberton, to
which it is connected by an aerial ropeway (Plate 1) and a
winding road some 25 miles long.   From Barberton, at an
elevation of about 3,000 feet, the road rises to over 5,000
feet before dropping down to the mine nestling at the foot
of the Emlembe Mountain.   The rainfall is over 90 inches

per annum and most of the small streams running down the ever-green, bush-covered kloofs are perennial.   The Tutusi River, which runs through the centre of the main quarry, has recently been diverted by means of a tunnel into a valley just east of the mine.   West of the mine the deep valley of the M'Sauli River runs south to open up in the broad valley of the Komati River some $4\frac{1}{2}$ miles from Havelock (Plate 4).   The M'Sauli Asbestos Mine is situated on the eastern side of the M'Sauli River about half a mile north of its junction with the Komati.

Geology (See Appendix 2)

The chrysotile asbestos deposit of the Havelock Mine occurs in a sill-like body of serpentinite belonging to the basic phase of the Jamestown Complex.   Pretorius (1948), who has made a survey of the general geology of this area, has suggested two periods of magmatic intrusion.   He considers the first period, now represented by basic schists, to be part of the Jamestown Complex, but the serpentinite, with some pyroxenite and diorite, is believed to be younger and grouped together as the Havelock Complex.   The reasons for this two-fold subdivision, as given by Pretorius, are the following:

1. The schistose texture which is so markedly developed in the Jamestown basic rocks is only found to a limited extent in the Havelock Complex.

2. Certain rocks of the latter still represent original rock types, while all the basic rocks of the Jamestown Complex are metamorphic types.

3. The serpentinite sometimes cuts across the Jamestown basic rocks into the Fig Tree Series.

4. The rocks of the Havelock Complex are differentiated while those of the Jamestown are not.

Pretorius further found that the structures of the Havelock Complex conform with those produced by the Archaean granite in the rocks of the Swaziland System;   that a large

number of pegmatites and quartz veins carrying tourmaline, associated with the granite, cut across the rocks of the Havelock Complex; that a tongue of granite cuts across diorite of the Havelock Complex and that the metamorphism of the rocks of the latter is more intense than certain dykes which are definitely younger than the granite. From this he came to the conclusion that the rocks of the Havelock Complex were emplaced before the intrusion of the granite and that they might represent the basic phase of the latter.

The present author feels, however, that the intimate association of basic schist with serpentinite throughout the Barberton Mountain Land, as well as the fact that the two rock types grade into one another, would indicate that the two-fold subdivision is not justified.   The differences in metamorphism, to which Pretorius refers, do not represent changes in the grade of metamorphism, but merely different behaviour in reaction to stress - a property dependant on the nature and original composition of the rock as well as on its tectonic setting.   The mineral assemblages both of Havelock and of Jamestown rocks indicate rather low grade regional metamorphism of the greenschist facies (Barth, 1952, p.334).

The Serpentinite

At the Havelock Mine the serpentinite is conformable with the rocks of the Fig Tree Series, all dipping at about 55° to the south.   East of the mine the serpentinite can be followed along strike to near the explosives magazines where an abandoned mine indicates the presence of at least some fibre.   In a valley south of this point are outcrops of serpentinite surrounded by massive cherts.   This serpentinite could be followed for some distance westwards, but does not seem to be continuous with the main serpentinite.

South of Windy Ridge serpentinite outcrops are found on the slope of the hill formed by the footwall chert and from there on to the site of the New African Village. The structure in this area is extremely complicated and very difficult to decipher due to the lack of outcrops.

Serpentinite also occurs in the valley south-east of the abattoir and again in the valley running from the New African Village towards the Steam Power Station. Outcrops of serpentinite can also be seen in the river bank just south of the Havelock – Piggs Peak road and in the valley north of the road where it continues for some distance between massive cherts. Veins of very short brittle fibre were found in this serpentinite. When deeply weathered the serpentinite closely resembles the basic schists. Coupled with the fact that the serpentinite sometimes grades into schist, this makes it very difficult to determine whether the serpentinite is continuous or not.

West of the Havelock ore-body the serpentinite is covered by the main waste dump and only crops out again west of the old sports field. From there it runs westwards through the nek between the footwall chert and some massive hangingwall chert. The serpentinite here must be very thin and appears to have been somewhat displaced. Westwards the serpentinite crops out continuously, between black and white cherts, into the valley of the M'Sauli River, where it is cut off by a large tear fault. Just before reaching the main fault the serpentinite is also displaced by a few small normal faults. Although several prospecting pits exist, only very short fibre was seen in a few places.

Further south there is a gap of nearly two miles where no serpentinite occurs. On the property of the M'Sauli Mine it appears again on the western side of the main fault, from where it continues intermittently through the Steynsdorp to near the main Oshoek – Mbabane road. An abandoned slip

fibre mine is situated on one of these outcrops, just south of the old Steynsdorp village.

The Havelock ore-body has a strike length of about 4000 feet and a width varying between 60 and 350 feet, the average being about 110 feet. The dip is about 55° south of southeast but steepens slightly in the deeper levels.

The ore-body is composed of light green, granular serpentinite which grades upwards into a darker green, more compact variety, with a corresponding decrease in fibre content. The hangingwall of the ore-body is thus determined by an economic pay limit. Specimens of the light green (V.22) and the dark green serpentinite (V.14) were selected for chemical analysis. The variation in total thickness of the serpentinite is difficult to assess since mining rarely penetrates far into the hangingwall. On 3rd Level near the main inclined shaft the thickness is over 300 feet but at 17E crosscut it is nearer 400 feet. Further east the thickness decreases and at 30E crosscut it is less than 200 feet.

An oblique strike fault cuts through the Havelock ore-body and has obscured the true thickness of the serpentinite as well as its relationships with the footwall. At the main inclined shaft the fault is in the immediate footwall, where it has caused extremely broken ground often associated with brown mud (see Appendix 3). Much concrete work has had to be done, both in the shaft and in crosscuts and drives, as a result of this fault. In 2E crosscut on 3rd Level the fault is well exposed. It here dips steeply to the south and the banded cherts have been pulled down against the fault indicating that it is a normal fault. It has not been possible to determine the throw on the fault. In the western section of the mine the fault, where it cuts through the ore-body, has caused extensive shearing of the serpentinite. Very little fibre occurs in this region. In the Tutusi deviation tunnel the presence of the fault is clearly seen by the intense shearing of the serpentinites.

Also on surface the fault can be traced without difficulty. In the excavations east of the Quarry office, as well as on the road to Windy Ridge, extensive shearing has taken place and in the vicinity of the New African Village a chert-hematite breccia marks the trace of the fault.

Several other smaller faults occur, as can be seen from the displacement of the chert bands (Appendix 2 and Plate 6). Underground these faults are difficult to detect due to the absence of marker beds. Several fissures extending for long distances are, however, found. These are usually filled with magnesite or calcite and often show "slickensides". It is therefore possible that they represent small displacements.

Along the western side of the New African Village and towards the abattoir, the footwall chert and schist, as well as the serpentinite, have been intensely ferruginized along one of these smaller faults. Also along the fault displacing the cherts north of Windy Ridge the serpentinite has been changed into a hematite-serpentine rock. The hematite occurs as finely disseminated grains as well as in the form of veinlets through the rock. Mehliss (1946, p.18) has examined these rocks as a possible source of iron ore, but has come to the conclusion that they are too high in silica and too low in iron.

The chrysotile asbestos in the Havelock ore-body occurs as a stockwork of crossfibre seams forming about 3 to 4 percent of the rock and varying in fibre-length from less than $\frac{1}{8}$ inch to, in rare cases, over 2 inches, with an average from around $\frac{1}{2}$ to $\frac{3}{4}$ inch. Although there is no pronounced orientation of the chrysotile seams, it would appear as if there is a tendency for the seams to occur in two distinct directions - one dipping at about 70° south and the other at about 15° north (Plate 5).

Petrography of the Serpentinite

The ore-body of the Havelock Mine consists of a light green, granular serpentinite which grades upwards into a more compact, darker green variety.   Under the microscope the lighter green variety shows colourless cores of "crosshatched" fibrous serpentine surrounded by veinlets of light yellow serpentine (Plate 17).   Brucite, in the form of grains as well as veinlets, is present in some places.   Veins of chrysotile cutting through the serpentine are also colourless Plate 18).   Ore, in the form of anhedral and subhedral grains, as well as in the form of stringers, is sparingly present. Many of these grains have dark borders with a translucent reddish-brown core with a high relief.   They are isotropic and probably chrome-spinel although no Cr_2O_3 is recorded in the chemical analyses (see later discussion under chemical analyses).   In a few cases the ore consists of a colourless isotropic core with a thin rim of opaque material or even several concentric rims.   This core may represent serpentine formed by alteration from the spinel (Plate 29).

The dark green serpentinite differs from the light green variety in that brucite was nowhere observed, while small amounts of talc and chlorite may be present.   The percentage of ore mineral is also greater (Plate 20).

In the 2E crosscut south on 4th Level the light green serpentinite is composed of isotropic or near isotropic grains of serpentine separated from one another and traversed by thin veinlets of serpentine with a higher birefringence. A small amount of carbonate (magnesite) is also present. Going north in this crosscut the isotropic cores gradually change into crosshatched, fibrous serpentine of the normal type.   In the drive west of 4th Level one specimen examined still contained small, partly altered remnants of a mineral which looks like olivine.   It has a high relief and a strong birefringence, but due to its small size it was impossible to determine the optical properties accurately.   The

supposed olivine is often surrounded by veinlets of serpentine.
Specimens of serpentinite collected from the 5th Level were
all composed of the normal vein-type of serpentine.

East, as well as west, of the Havelock Mine the
serpentinite is similar to the light green variety of the
ore-body, the only difference being that it carries no or
very little fibre.   Irregular bodies of the darker green
variety do, however, occur.   The outcrop along the road just
east of Windy Ridge was seen to contain, in thin section,
remnants of clino-pyroxene of diopsidic composition, in a
finely fibrous matrix of serpentine and needle-like tremolite.
A small amount of talc and dolomite is also present.

The sheared serpentinite, which is encountered on the
road south of Windy Ridge, as well as in the Tutusi deviation
tunnel, is seen in thin section to be composed of veinlets of
birefringent serpentine alligned parallel to one another.
Thin seams of chrysotile are occasionally observed cutting
across the foliation (Plate 24).

The partly ferruginized serpentinite from the valley
south-east of the abattoir is composed of the normal vein
type serpentine.   Hematite staining along fractures, as well
as veinlets and stringers of hematite, can be seen (Plate 25).
The seams of chrysotile, however, have been changed in places
to a mineral which is pleochroic from brown to light brown,
with the strongest absorption when the fibres are parallel to
the lower nicol (Plate 32).   This brown mineral also has a
slightly higher birefringence than chrysotile and may be
ferro-chrysotile (Nagy and Faust, 1956, p.817).

Talc-carbonate rock

At several places the serpentinite of the Havelock ore-
body was found to grade gradually into a talc-carbonate rock.
No sharp contact could be observed and under the microscope
it could be seen that replacement begins with the appearance
of grains of carbonate (magnesite) (Plate 27).   As the

carbonate increases, small flakes of talc also appear, gradually replacing the serpentine until the rock is composed entirely of talc and carbonate (Plate 27). In places the talc is present only in very small quantities or even absent altogether, so that the serpentinite is replaced by a pure carbonate rock. In one specimen secondary wisps of serpentine were noticed in the calcite (Plate 26). Similar transformations at the Shabani Mine in Southern Rhodesia are considered by Keep (1929, p.105) to be due to shearing stresses developed during the hydrothermal stage of granite intrusion. It is interesting to note that at Havelock the talc-carbonate rocks usually occur in the western section towards the footwall of the ore-body i.e. close to the large strike fault. Good exposures are found in the upper portion of the main inclined shaft, in the foot-wall drive west on 3rd Level and in the footwall drive west on 5th Level. The talc-magnesite rocks are, however, not restricted to the footwall and may also be found towards the hangingwall, as in the western quarry and in 26E and 30E crosscuts on 3rd Level.

Rocks of the Fig Tree Series (see Appendices 3 and 4)

The footwall rocks of the Havelock ore-body consist of a great thickness of shale overlain by a massive chert band over 200 feet thick. The shale weathers very easily and is usually covered by a thick covering of soil. It is well exposed, however, in the adit put in for for the new vertical shaft as well as in the Tutusi deviation tunnel. In both cases it shows pronounced shearing and may be better termed a phyllite. Under the microscope it can be seen to consist of very fine-grained sericite and chlorite with angular fragments of quartz and many thin, secondary quartz veins.

The chert is usually massive and either black or white, but may in places be composed of thin alternating black and white bands. On 5th Level, in the footwall drive west, the

chert consists of a handsome rock composed of alternating bands of green and black. The footwall chert was also exposed in 17E, 20E and 30E crosscuts north on 3rd Level, in the 2E crosscut north on 4th Level, while the crosscut north from the sub vertical shaft on 4th Level went through the chert into the footwall shale. The position of the chert has been further established by diamond drilling at several places. A normal fault with a downthrow on the east has thus been shown to exist on 3rd and 4th Levels between the crosscut from the sub vertical shaft and the 2E crosscut.

The serpentinite is usually separated from the chert by a variable thickness of talc-carbonate and talc-carbonate-chlorite schist. A rock composed of carbonate and quartz with lesser amounts of chlorite also occurs above the chert (20E crosscut, 3rd Level). In the crosscut south, near the inclined shaft on 3rd Level, a sandy shale, composed of chlorite and irregular grains of quartz, together with a grey carbonate rock occur between the chert and the serpentinite. In some places the serpentinite is separated from the chert by an extremely fine-grained amphibolite composed of needle-like, colourless tremolite with minor quantities of chlorite.

It is not always possible to determine whether the schists belong to the Fig Tree Series or whether they have formed by alteration from the serpentinite.

The rocks following on top of the serpentinite are also composed of alternating bands of chert and schist belonging to the Fig Tree Series. On surface the schists seldom crop out and their position is marked only by depressions between ridges of chert. Underground, the mine workings seldom penetrate the hangingwall sediments. In 10E crosscut south on the 3rd Level black chert with shale and a green schist composed of talc, carbonate, chlorite and colourless amphibole, with patches of fine quartz, occur. The dip here is 65° south. The drainage adit on 3rd Level, however, gives

an excellent cross section of the hangingwall rocks.
Directly on the serpentinite follows a fine-grained rock
composed mainly of amphibole.   This is overlain by massive
black chert, slightly banded in places and varying in
thickness from 20 to 50 feet.   On this chert follows about
60 feet of quartz-sericite-carbonate schist, often with
pyrite.   The schist is in places replaced by irregular
veins of chert and small lenticular chert bands are found
to cut across the schistosity.

On top of the schist follows another black and grey
chert which is faintly banded in places.   This chert is
overlain by a great thickness of alternating talc-carbonate
and chlorite schists, arenaceous shale and massive chert.
In the Tutusi deviation tunnel a rock consisting of
alternating light and dark bands was observed interbedded
with the hangingwall schists.   The width of the bands varies
from about 2 inches to less than a tenth of an inch.   Under
the microscope the light bands are seen to consist of fibrous,
colourless amphibole and the dark bands of grains of magnetite
with interstitial amphibole.

Hypabyssal rocks

In the upper portion of the serpentinite, near its
contact with the overlying sediments, occurs an intrusive
sill known as the "Hangingwall Sill".   It is persistent
throughout the mine but extremely irregular in thickness.
It may split into as much as 3 separate bodies (see Appendix
4), and may vary from 40 feet thick on one side of a cross-
cut to less than 20 feet on the other.   In the hand specimen
the rock appears coars-grained but under the microscope it is
seen to be composed of extremely fine-grained needles of
colourless amphibole with small amounts of epidote and
irregular patches of near-isotropic chlorite.   In some
specimens remnants of original pyroxene and in others faint
relics of twinned plagioclase and an ophitic texture can be
seen.   In a few cases the rock was found to be porphyritic,

with phenocrysts of a light green amphibole set in a fine-grained matrix of fibrous amphibole and untwinned plagioclase (Plate 36). Veinlets of fibrous amphibole traverse the rock in places.

Several crosscutting dykes also occur at Havelock. They too are extremely variable in thickness and in shape as can be seen, for instance, in 17E crosscut on 3rd Level. One of these dykes in the mid-west drive on 3rd Level is composed of unaltered pyroxene with a low birefringence and completely altered laths of plagioclase. The original ophitic texture is still well preserved, but the plagioclase is represented only by an aggregate of extremely fine alteration products.

A similar dyke from the 20E tramming drive on 3rd Level is composed of large crystals of a weakly pleochroic amphibole set in a matrix of fine-grained clino-zoisite and calcite. Original plagioclase showing polysynthetic twinning can be faintly observed in places.

A dyke with outcrop on surface near Windy Ridge was found to consist of large euhedral to subhedral crystals of augite which are often twinned. Some of the pyroxene is altered to uralite. The interstitial plagioclase, however, has been completely saussuritized and secondary quartz is present in fair amounts. The rock is medium-grained and has a hypidiomorphic texture.

It has not been possible to determine the relative ages of these dykes, but they were found to be displaced by small faults at several places.

Along most of the dykes the green serpentinite has been changed for several feet to a reddish-brown rock. Under the microscope this so called "chocolate serpentine" is seen to consist of isotropic or extremely fine-grained serpentine with a large amount of disseminated ore - mainly hematite but also some magnetite in the form of stringers. In most cases the chrysotile veins petered out on entering the brown

serpentinite, but in a few cases fibre of inferior quality
was noticed up to the dyke.   Under the microscope it could
be seen that the fibre had been recrystallized to a fine-
grained aggregate in patches.

Although the evidence is not conclusive, it would appear
that some of the dykes were pre-fibre while others were
intruded after fibre-formation.

Mining

The Havelock ore-body is mined by a type of sub level
caving.   At the time of this investigation mining operations
had reached the 5th Level, a depth of approximately 600 feet
below surface.   The fibre was still of good quality.
Unfortunately many of the higher levels were already
inaccessible.   The far eastern section on 3rd Level, where
ventilation had been stopped, could only be given a brief
visit.

The M'Sauli Asbestos Mine

The serpentinite, within which the ore-body of this
mine is situated, is very similar to that of the Havelock
Mine, dipping here at about 60° to the east.   At the time
of the author's visit only little development had been done.
The best fibre seemed to occur in the northern section of
the mine towards the large fault running along the valley
of the M'Sauli River.   As in the case of Havelock, massive
chert of the Fig Tree Series forms conspicuous outcrops
both in the footwall and the hangingwall of the ore-body,
but no excavation had been made to expose the argillaceous
rocks.   The fibre is also of the same high quality as that
of Havelock, but a higher percentage of magnetite seemed to
be associated with it.

The serpentinite, in which the fibre of the M'Sauli
Mine occurs, continues southwards through the Komati River,
but has not been followed by the author.   Near the old
Steynsdorp village, however, an abandoned chrysotile mine

occurs in a serpentinite interbedded between cherts, similar to Havelock and M'Sauli. This serpentinite is presumably a continuation of the Havelock-M'Sauli serpentinite. The only fibre which could be found by the author was a small amount of slip fibre, although Hall (1930, p.220) mentions that fibre of fair length had been found near the surface.

Further south, near the Oshoek - Mbabane road, prospecting operations have been carried out in a dark green serpentinite, but, as far as the author could ascertain, only small amounts of fibre of inferior quality have been obtained.

2. THE NEW AMIANTHUS, MUNNIK MYBURGH AND SUNNYSIDE MINES

From just north of Kaapsehoop a belt of rocks, approximately 1 to 2 miles wide and belonging to the Fig Tree Series and the Moodies System, runs in an east-west direction along the northern boundary of the Kaap Valley Granite (Appendix 1). In these rocks occur sill-like bodies of serpentinite and diorite belonging to the basic phase of the Jamestown Complex. The serpentinite is composed mainly of the hard blue variety, but towards the western end, just before the ancient rocks disappear underneath the younger Godwan Formation, light green serpentinite is found alternating with the hard blue variety (Appendix 5). It is in this light green serpentinite, often along the contact with the blue variety, that the chrysotile asbestos deposits, worked by the New Amianthus Mine, the Munnik Myburgh Mine and the Sunnyside Asbestos Mine, occur.

The New Amianthus Mine is situated about 3 miles due north of the small village of Kaapsehoop, with the Munnik Myburgh Mine approximately 3 miles to the east of the latter. The Sunnyside Asbestos Mine is again situated about 3 miles east of the Munnik Myburgh Mine. The asbestos

deposits of all three mines occur in light green serpentinite belonging to the Jamestown Complex. These sill-like serpentinite bodies alternate with a hard blue-green variety and the whole sequence has been thrown into a gentle syncline and anticline (Hall, 1930, p.111).   The dip of the bodies is to the north at angles which vary from 30° to vertical, while the strike of the serpentinite is more or less east-west.

At the New Amianthus Mine the serpentinite is overlain by the rocks of the Godwan Formation (correlated with the Ventersdorp System by Hall (1930, p.110), but now considered to be the equivalent of the Dominion Reef System (Truter, 1950)).   These rocks, which consist of a thin impure quartzite at the base, followed by a thin layer of slate and a great thickness of greenish amygdaloidal lava, dip westwards at angles varying from 10° to 40°.   The basal quartzite forms a conspicuous outcrop, very useful as a "marker" since the "Ribbon-line", the principal fibre horizon of the New Amianthus Mine, lies close below and approximately parallel to it.   The asbestos seams are usually found within the first 15 feet from the contact between the quartzite and underlying serpentinite. Occasionally a thin basic sill separates the sediments from the serpentinite and thus the hangingwall in various parts of the mine is either quartzite or this basic sill.

In the Munnik Myburgh and Sunnyside Mines the fibre horizons are situated in the light green serpentinite along its contact with the blue-green variety.

Three sill-like bodies of light green serpentinite occur on the property of the Munnik Myburgh Mine giving rise to five fibre horizons known (from north to south) as: the "Munnik" line, the "North" line, the "Smithy" line, the "Griffin" line (at one time also worked on the property of the New Amianthus Mine) and the "Jones" line (Appendix 5).

Of these, the "Munnik" and "Griffin" lines are the most
important. On the north side of the mine the "reefs"
are cut off by a curved fault (known on the mine as the
"Hamilton" fault) which dips steeply to the south (Fig.1A).
The result is that all the "reefs" will probably terminate
against the fault in depth. It is interesting to note that
in the vicinity of the fault the normal "ribbon" nature of
the fibre of the "Munnik" line is replaced by a stockwork of
asbestos seams, over an area 50 feet wide and nearly 200
feet long.

The fault which cuts across the serpentinites at the
Sunnyside Mine some 3 miles west of Munnik Myburgh is probably
the same against which the fibre horizons terminate at the
latter mine. The main horizon worked at this mine would
then be the equivalent of the "Griffin" line (Appendix 5).

At the Amianthus Mine the main fibre horizon known
as the "Ribbon" line runs north-south, parallel to the
contact of the serpentinite with the basal sediments of
the Godwan Formation. The horizon thus cuts across both
the light green and the dark blue-green varieties. From
the stoped areas (Appendix 5) it can be seen that fibre
occurred in payable quantities only where the light green
serpentinite was in contact with the sediments. In
depth, below the 8th Level, the serpentinite terminates
against basic schist (Fig.1B). It is interesting to
note that the asbestos of the "Griffin" line, the fibre
found at the Sunnyside Asbestos Mine and the fibre of
the southern section of the "Ribbon" line all have similar
characters - a fact which is consistent with their
occurrence in the same serpentinite. The fibre is often
honey-coloured, and associated with barbertonite and stichtite[*];

[*]The mineral described by Hall (1921) as stichtite was re-
examined by Frondel (1941, p.295). He found that the material
actually consisted of two minerals intimately intergrown.
From X-ray data it was established that the one mineral is
rhombohedral and corresponds to stichtite, while the other
mineral is hexagonal. The name barbertonite was suggested
for this new mineral.

it often peters out in patches of brown (chocolate)
serpentinite and often consists of a few seams of long
fibre associated with a great number of very thin parallel
seams (Fig.2).

Nearly all of the "Ribbon" line has been worked out.
The mine has been closed down for many years and as a
result most workings are inaccessible.   It is believed,
however, that it will be re-opened again in the near future
to reclaim certain areas in which fibre still exists.
Hall (1930, p.116) gives a detailed description of the
nature of the "Ribbon" line.   Over seven feet the upper
3 feet contained 15 seams per linear foot with fibre length
varying between $\frac{1}{2}$ and $\frac{1}{4}$ inch.   The lower four feet contained
30 seams per linear foot with fibre lengths between $\frac{1}{4}$ and
one-sixteenth of an inch.   Over this seven feet the rock
contained about 40% of fibre.   Underlying this "ribbon"
rock the number of seams per linear distance (seam density)
was much less but the length of the fibre increased.   Fibre
lengths of 2 to 4 inches were not uncommon, and in one case
fibre of up to 8   inches was measured, though it contained
a plane of discontinuity.   This development of fibre is
certainly exceptional and nowhere else has the author seen
a similar occurrence.

3. STERKSPRUIT, STOLZBURG AND DOYERSHOEK ASBESTOS MINES

The Sterkspruit Mine

In the Komati valley on the farms Sterkspruit 239,
Stolzburg 202 and Doyershoek 145, sill-like bodies of
light green serpentinite, allternating with layers of
dark blue-green serpentinite occur.   These rocks, which
also belong to the basic phase of the Jamestown Complex,
are surrounded by sediments of the Fig Tree Series and the
Moodies System.   On the farm Sterkspruit 239, which
consists of open flat country with a few rugged koppies,

chrysotile of good length and quality (seams up to 1 inch) was seen in an adit on one of the koppies. The percentage of fibre, however, seemed to be low. Also on the flats in some rather dangerous pits, dug down to depths of over 20 feet, fibre of good quality and measuring from $\frac{1}{2}$ to $\frac{3}{4}$ inch in length was seen. Too little development had been done at that stage, however, to get an idea of the extent of the deposit.

East of Sterkspruit, on the farms Stolzburg and Doyershoek the country becomes more mountainous with a series of ridges running approximately east-west. On the southern portion of Stolzburg the ridges are built of quartzite of the Moodies System, while the valleys are occupied by shale. These sediments have been folded into what van Eeden and his co-workers (1956, p.76) call the Stolzburg syncline. The dip of the beds is steeply inward except at the western extremity where the southern limb is overfolded. The syncline, which plunges to the west, is here truncated by an oblique fault which has brought Fig Tree shale up against the Moodies sediments.

The northern portion of Stolzburg is covered mainly by serpentinite and some diabase belonging to the Jamestown Complex. The ridges here are due to the more resistant blue-green serpentinite (altered pyroxenite) which occurs as parallel sills in the lighter green variety.

The Stolzburg Mine

At this mine, along the southern slope of a ridge formed by altered pyroxenite, the chrysotile asbestos occurs in light green serpentinite (known on the mine as boulder series). Fibre is found over a distance of 9000 feet but has been produced economically only from a few isolated places (Appendix 7). The pyroxenite forming the top of the ridge is only between 40 and 50 feet wide, but occurs along the whole length of the property. The dip

of the dyke, as proved by diamond drilling, is very steep.
Normally it is to the south at angles between 70° and 80°,
but one borehole (BHX-7) indicated a steep dip (80°) to the
north.   At a few places the dyke has been displaced by
small faults and north of Central Quarry it is duplicated
for some distance.   The Road Quarry is situated between
the two dykes.   In the vicinity of these displacements
the serpentinite is found to be intensely sheared.

In outcrop the pyroxenite is easily recognised by its
reddish colour and granular appearance as against the
pitted surface of the serpentinite.   The latter usually
has a dark grey colour, but may appear lighter green where
it has been subjected to shearing.

Under the microscope the outlines of the original
pyroxene crystals can still be seen although the rock now
consists mainly of fibrous, colourless amphibole (tremolite),
green chlorite and irregular patches of near-isotropic
serpentine.   A little talc and carbonate have been noticed.
In a few specimens remnants of pyroxene, altering to
amphibole, occur.   The optical properties of the pyroxene
were not easily obtained owing to the small size of the
remnants and to their altered state.   From determinations
made with the Universal stage it would appear that it is
a clino-pyroxene ($2V = 54^{\circ}$ $Z \wedge C = 44^{\circ}$) even though the
birefringence is on the low side (1st Order yellow and red
interference colours), (Plate 41).

At the Hill Top Quarry, situated at the eastern
extremity of the deposit, chrysotile asbestos occurs in
an unusual and interesting manner.   The serpentinite
here consists of spheroidal "boulders" which have a core
of dark green serpentinite surrounded by a rim of lighter
green serpentinite.   The contact between the core and the
rim is usually sharp (Fig.3 and Plate 10).   In the light
green serpentinite seams of chrysotile asbestos, with
average fibre lengths of between $\frac{1}{8}$" and $\frac{1}{4}$", but occasionally

as long as $\frac{1}{2}$" or even $\frac{3}{4}$", occur in the form of concentric shells. A large amount of magnetite is often associated with the fibre. In some cases the dark green core is absent and the whole "boulder" consists of the lighter green variety.

It seems fairly certain that the light green serpentinite has formed from the darker green variety - probably by solutions which entered the rock along fractures. At the same time, or somewhat later, the asbestos must have formed in the lighter green serpentinite. In thin section the two types have entirely different textures (Plates 38, 39 & 40). The dark green core consists of vein-type serpentine, often in the form of oval grains lying in a matrix of structure-less serpentine. This pattern is reminiscent of that of olivine grains included in pyroxene, even to the extent of showing radiating expansion cracks. The light green serpentine, on the other hand, assumed to have been derived from the same original rock as the dark green variety, is composed of grains of serpentine showing crosshatched texture. Apart from the larger chrysotile veins, no vein type serpentine could be seen under the microscope. This would indicate to the author the danger of deducing the nature of the original rock from the texture of the altered equivalent. Ore in the form of stringers and grains as well as octahedra of chrome-spinel were found in both specimens but more abundantly in the darker variety. The boulder formation is best developed in the Hill Top Quarry and is nearly absent from the rest of the property.

The fibre in the central section (below Central Quarry) is in the form of a stockwork, although a tendency for parallel arrangement of seams ("Ribbon" type) was noticed at many places. In the northern face of the Hill Top Quarry the distribution of fibre (and of the boulders) forms an interesting pattern (Fig.3). The large number of parallel seams end abruptly against slip

planes and small faults which in themselves carry no fibre but are usually filled with picrolite and magnesite. Often the fibre veins show a definite drag against the faults but the fibre itself is not disturbed. It would appear, then, that the fractures in which the asbestos occurs were formed as a result of the faulting and that, since no crossfibre is found in the faults, the fibre grew in these fractures during the formation of the latter; in other words, while there was still movement in the faults and tension in the fractures.

A fine-grained dense rock, called "silicified serpentine" by the miners, was found to consist of small interlocking grains of pyroxene and amphibole without any quartz. The rock is surprisingly fresh but the minerals were too small for determination of their optical properties by means of the Universal stage. Only loose boulders and no outcrop of this material could be found and it may represent the chill phase of the pyroxenite, although no sign of such was noticed in the borehole cores. Alternatively it could represent younger pyroxenitic dykes.

Several dykes of diabase cut through the serpentinite. On surface they are not easily detected because of a thick covering of serpentinite and pyroxenite scree. Loose boulders of diabase are, however, found at many places. Diabase has also been intersected underground at several places in the central section. Although irregular in shape, some of the diabase occurrences seem to strike approximately east-west (sills), while others are in the form of dykes with roughly a north-south trend. At the entrance of the adit to the underground workings diabase is encountered for nearly a hundred feet. Diabase of great thickness was also intersected in some of the diamond drill holes. Borehole W.4 went through diabase for the first 150 feet while borehole Y.3 intersected nearly 100 feet of it.

In thin section these diabases are composed of green
amphibole with extremely altered plagioclase.   Faint
twinning could still be seen in some grains and the extinction
angles indicated a composition of about 40% anorthite.   In
a few specimens chlorite, talc and quartz in intergrowth with
felspar were observed.   The age of the dykes is uncertain.
They might be younger than the pyroxenite although no sign
of diabase was seen in the gaps in pyroxenite ridges.   A
large diabase dyke north of Hill Top Quarry ends abruptly
against the serpentinite.   Whether it has been displaced
by faulting could not be determined.

The serpentinite adjoining the diabase in the under-
ground workings has been changed to a dark brown variety
(chocolate serpentine) similar to that of the Havelock Mine.
No fibre was noticed in this serpentinite.   North of the
serpentinite a number of diabase sills occur interbedded
with sediments of the Fig Tree Series (not shown on Appendix
7).   This diabase varies considerably in texture.   It may
be fine- and even-grained or consist of long needles of
hornblende in a matrix of altered plagioclase.   Clino-
zoisite is found as small crystals in the felspar.

At several places underground in the central section,
as well as in the immediate hangingwall of the ore-body in
the Hill Top Quarry, leucocratic dykes (called felspar by
the miners), up to 10 feet thick, were encountered.   These
dykes also have dark brown serpentine along their borders,
but fractures in this serpentine are filled with short
fibre which would indicate that the dykes are pre-fibre in
age.   In thin section the rock is seen to consist of
colourless diopside, clino-zoisite and irregular patches
of garnet.   The latter mineral occurs as aggregates of
small crystals some of which are weakly birefringent.
Large grains of sphene are sparingly present.

A thick pyroxenite "dyke" occurs east of the Stolzburg
Mill, but its relationship to the pyroxenite sill and to

the serpentinite could not be determined from the poor outcrops.

Just south of the Hill Top Quarry pyroxenite is also encountered, but it ends abruptly when followed westwards. Intense shearing of the serpentinite can be seen at this point as well as further in the direction of the mill. Although the pyroxenite dyke does not seem to have been displaced by the shearing, the position of the pyroxenite south of Hill Top Quarry would indicate that faulting has taken place along this zone.

The Doyershoek Mine

The serpentinite of Stolzburg extends north-eastwards into the adjoining property, Doyershoek, where chrysotile has also been mined on a small scale. Although the "Boulder formation" is also evident at this mine, it is not as well developed as in the Hill Top Quarry at Stolzburg, and the fibre occurs more in the form of a stockwork.

Magnetite was found associated with most of the fibre and in one spot the asbestos was intimately associated with veins of dark-coloured opal.

4. BARBERTON CHRYSOTILE MINE (Fig.4)

This mine is situated on the farm Koedoe 332 and lies about 4 miles due south of Magnesite Siding on the railway line between Kaapmuiden and Komatipoort.

The chrysotile asbestos again occurs in serpentinite belonging to the basic phase of the Jamestown Complex. The serpentinites take the form of sill-like bodies surrounded by amphibole schist and have been folded into a syncline pitching to the east. On the south-east the serpentinite abuts against near vertical slate and chert of the Fig Tree Series of the Swaziland System.

The chrysotile was originally mined in a number of opencast workings but at present most of the mining is done underground at deeper levels.

The ore-body, which varies in width from 35 to over 100 feet, dips at angles from 30 to 40 degrees to the north and to the north-east. Most of the fibre, which may be up to an inch in length, but averages around $\frac{1}{4}$ to $\frac{1}{2}$ inch, is in the form of a stockwork. "Ribbon" type of fibre is also found and is usually considered by the miners to indicate the proximity of either the hanging or footwall. Thin veins of magnetite and magnesite are often found associated with the fibre seams. In one place a vein of dense, smooth apple green serpentinite with specks of magnetite and bordered by thin veins of asbestos, was seen to grade into fibre over a short distance. Although most of the fibre veins are in the form of a stockwork, parallel lenticular seams with en echelon structure occur quite frequently.

At one place a seam of pseudo-fibre similar to the "painted veins" of Cooke (1937, p.134) was noticed. In the hand specimen it was not possible to separate the fibres from one another. Under the microscope, however, it can be seen that the rock consists of bundles of fibrous serpentine, often radiating but usually parallel to one another, set in an isotropic matrix of serpentine (Plate 42).

5. KALKKLOOF ASBESTOS MINE

On the farm Kalkkloof 250, which lies in a straight line about 6 miles north-west of Badplaas, a tributary of the Komati River known as the Assegai Loop, has cut down through the dolomite of the Transvaal System, exposing an irregular floor of serpentinite, amphibolite and amphibole schist of the basic phase of the Jamestown Complex (Appendix 6 and Plate 11). A fault-dyke cuts through the serpentinite in a north-south direction. At the mine

the dyke follows the course of the Assegai Loop and good outcrops are encountered.   The rock is extremely fine-grained with a smooth black surface in contrast to the pitted surface of the serpentinite.   Southwards it leaves the river and is covered by serpentinite scree.   A few rounded boulders next to the road at the Manager's House mark its position;   further south the depression in the Transvaal sediments clearly shows the trend of the dyke.

In thin section the rock is seen to be quite fresh and composed of augite, labradorite with a small quantity of olivine.   It is holocrystalline, has a well developed ophitic texture, and is therefore a typical dolerite. From its freshness, mineral composition and the fact that it cuts the Transvaal System it is believed to be of Karroo age.

The serpentinite consists of alternating sill-like bodies of light green and dark green varieties.   They trend north-north-east and dip at about 60° west-north-west. Chrysotile asbestos, in the form of parallel seams, has developed in the light green serpentinite at the contact with the dark green variety.   Most of the fibre occurs on the western side of the fault-dyke, and to date only two small occurrences known as the Munnik Lode and the Compound Lode have been found east of the dyke.   In an adit on the Munnik Lode the contact between the dolerite and the serpentinite is well exposed.   On the western side, the following zones have been recognised from the bottom upwards: the Millsite Lode, the X-Lode, the Main Lode, the New Lode and, right at the top, the Amianthus Lode, (Fig.5A).   Of these, the X and Main Lodes are the most important fibre-bearing zones.   An inclined shaft, dipping at about 30 degrees, has been put down in the light green serpentinite between the two lodes and crosscuts have been driven approximately every 200 feet along the incline. The horizontal distance between the two lodes varies from 200 to 250 feet.

The Main Lode is about 5 feet wide on the average, but it may be wider or may pinch out to a mere trace of fibre. In some places it was seen to split up into two separate zones around boulders of dark green serpentinite. The fibre is usually of the ribbon type with a large number of very thin parallel seams with a few (usually two) seams of greater length - even up to one inch (Fig.5B). This arrangement reminds one strongly of the Ribbon Line of the Amianthus Mine, as well as the Griffin Line of the Munnik Myburgh Mine. The Main Lode, being at the top of the light green serpentinite, has dark blue-green serpentinite as its hangingwall while in the X-Lode the latter forms the footwall.

In thin section the light green serpentinite is seen to be composed of normal vein type serpentinite with magnetite in the form of stringers and orientated veinlets. Octahedral grains of chromite (or chrome-spinel), which have been replaced by barbertonite, were noted in the serpentinite between the X and Main Lodes on 3rd Level. In most cases a thin rim of magnetite surrounds the barbertonite and in some magnetite also occurs in the centre of the grain, (Plate 43). Veinlets of barbertonite also exist.

On 1st Level the serpentinite between the X and Main Lodes has been replaced nearly completely by carbonate. Remnants of serpentine, with small amounts of talc and magnetite skeleton crystals, are found in a fine-grained calcareous matrix.

The dark green serpentinite between the Main and New Lodes on 3rd Level is composed nearly entirely of finely divided talc and needle-like amphibole with only a few remnants of original serpentine. Octahedra of chrome-spinel still exist.

Several crosscutting diabase dykes are found in the
underground workings.   One of these is exposed on surface
between the X and Main Lodes.   It is composed of augite,
long prismatic crystals of hornblende and partly altered
laths of plagioclase (An_{40}).

The fibre development at the Kalkkloof Mine is confined
almost entirely to the western side of the main dolerite
dyke.   Asbestos has been mined in the Main and X Lodes for
several thousand feet along strike.   The actual distance
from the furthest working to the fault-dyke is, however,
not more than a few hundred feet.   As will be pointed out
later, the author is of the opinion that a genetic
relationship exists between the faulting and the formation
of chrysotile asbestos.

<center>B   OCCURRENCES OF CHRYSOTILE ASBESTOS IN
THE SERPENTINIZED DOLOMITE OF THE TRANSVAAL SYSTEM</center>

General

As already pointed out earlier, the Dolomite Series
of the Transvaal System in the Eastern Transvaal decreases
in thickness from nearly 2000 feet near Pilgrim's Rest to
just over 100 feet at Carolina.   It is composed mainly of
massive dark grey dolomitic limestones.   Chemical analyses
of dolomite from various parts of the Transvaal indicate
that the rocks are nearly always dolomitic limestone rather
than true dolomite (van Eeden et al., 1956, p.105).

Lenticles and bands of chert are found at various
horizons in the dolomite.   Near the base of the Series
they are usually thin, but higher up in the succession
they become more massive and may be as thick as 30 feet
(Giant Chert).

In the northern portion of the area great thicknesses
of dolomite with typical "elephant's hide" weathering, are
often exposed in krantzes but in the extreme south, owing

to the thinly bedded nature of the dolomite, outcrops are much scarcer. Shales are occasionally found interbedded in the dolomite.

The rocks of the Dolomite Series rest on quartzite of the Black Reef Series and are overlain by the members of the Timeball Hill Stage of the Pretoria Series. The latter is composed mainly of shales and quartzites but a chert breccia, known as Bevet's conglomerate, occurs at the base of the series just above the dolomite. In the south of the area the conglomerate becomes more arenaceous and is locally known as the Rooihoogte Quartzite. The latter usually forms a prominent outcrop and between the two quartzites the Dolomite Series is therefore well defined.

Along several horizons in the dolomite, sheets of diabase, probably of Bushveld age, have been intruded. They vary in thickness from a few to over 150 feet and normally follow the bedding of the sediments for long distances. In many cases, however, it has been observed that a sill gradually transgresses across the bedding, so that at one place the sill may be in contact with massive dolomite while some distance away it lies against thinly bedded cherty dolomite.

In thin section the diabase is seen to consist of partly altered augite with laths of saussuritized plagioclase. A pronounced ophitic texture is usually present. Small amounts of biotite, chlorite, hornblende, magnetite and quartz were also noticed.

The dolomite in contact with these sills has usually undergone a certain amount of metamorphism. In the case of thin sills it is negligible, but with the thicker ones alteration of the dolomite up to several feet from the contact has been observed. The first change is normally the transformation of the grey dolomitic limestone to a whitish rock with less magnesium, i.e. a process of de-dolomitization. At many places streaks and bands of

greenish or brownish resinous serpentine, a few inches wide, are found in this altered dolomite. The position of the serpentine relative to the sill is variable. It may either be directly in contact with the diabase or may occur up to 4 or 5 feet away from the sill separated from the latter by whitish or greenish limestone. In some cases the zone of serpentine, which is normally parallel to the bedding of the dolomite, may end abruptly to continue again on a different horizon either closer to or further from the diabase. Several parallel bands of serpentine may also occur.

Where serpentinization of the dolomite has been caused by a dyke cutting across the bedding, the serpentine does not occur in parallel zones but is found to be distributed as irregular patches decreasing away from the diabase.

In the bands of serpentine associated with sills, chrysotile asbestos is sometimes developed. There are seldom more than one or two parallel seams but the fibre is often of fair length and excellent quality. The asbestos is normally restricted to the bands of resinous serpentine, but occasionally fibre may occur in greenish limestone (serpentine-calcite rock).

In the case of serpentine associated with dykes, the fibre may be found as a great number of seams ("Ribbon" type) parallel to the dyke. However, an occurrence outside the present area is known to the author where chrysotile asbestos has developed in a different way in dolomite next to a dyke. In this case the seams of fibre are parallel to the bedding of the dolomite and occur at several horizons for a few feet on either side of the dyke.

1. CONGO-VAAL ASBESTOS MINE

This mine is situated on the farm Rietfontein 70 which lies about 22 miles due east of Carolina (Appendix 8). The fibre occurs in the serpentinized dolomited just above

the upper contact of a diabase sill which is exposed in a
wooded kloof on the northern side of Zeekoei Spruit.   Hall
(1930, p.154) describes two occurrences on Rietfontein, the
one on the Kalkkrans horizon somewhere in the middle of the
dolomite succession, and the other on the Belfast horizon
some hundred feet lower down.   The zone on which the Congo-
Vaal Mine is situated, corresponds to the Belfast horizon.

Although serpentinization of the dolomite exists all
along the upper contact of the sill chrysotile fibre is
restricted to two occurrences.   The one is situated on
portion E of the farm, while the other occurs on portion F.
The best fibre has been obtained from the latter deposit.
Diamond drilling has also been carried out to investigate
the lower contact of the sill but, as far as the author is
aware, no fibre was encountered.   The thickness of the sill
is also not known since its lower contact is nowhere exposed.

In the kloof between the two deposits a dyke of diabasic
composition is well exposed striking in a NW-SE direction.
If the position of the upper contact of the diabase sill be
compared on the two sides of the dyke, it can be seen that
a certain amount of displacement must have taken place along
the dyke.   A number of small faults were also encountered
underground in both the E and F sections.   Along one of
these faults in F section the dolomite has been sheared and
crushed with the production of a dark mylonitic rock type.
Along the southern contact of the dyke a peculiar reddish-
grey friable sandstone up to several feet thick, was noticed.
Intimate mixing between the sandstone and the dyke, with the
production of hybrid rocks, has taken place along their
contact.   Whether the presence of this "sandstone dyke" is
purely accidental or whether it is of any significance in
relation to the origin of the fibre, is not yet certain.

The dip of the dolomite is at a low angle to the west
but small folds (known as rolls on the mine) are quite
common.   Unlike the case of blue asbestos (crocidolite)

within banded ironstone host rocks, these rolls do not seem to have any connection with the distribution of fibre.

Fibre of extremely good quality and up to 6 inches in length has been worked in both sections of the mine for several hundred feet down dip and is still persistent in depth, contrary to Hall's expectations (1930, p.155). Laterally, however, the fibre peters out and the mineralized zone seems to be restricted to the vicinity of the faulted area. The deepest portion of the mine would be more than 400 feet below surface.

The metamorphosed dolomite consists of irregular bands of greenish and yellowish limestone alternating with zones of resinous serpentine in which the fibre is found. A band of brownish serpentine, which is often associated with the fibre, has been analysed chemically (Sample V.168) and was found to contain a high percentage of iron and alumina as well as a fair amount of carbonate.

In thin section the greenish limestone was seen to consist of extremely fine-grained calcite with irregular patches and wisps of serpentine. The resinous serpentine is near-isotropic under the microscope but occasionally shows very weak birefringence with anomalous blue interference colours. A specimen of partly serpentinized dolomite containing some fibre was examined in section and seen to be composed of fairly large interlocking grains of calcite, with unorientated tufts of fibrous serpentine spread evenly through the rock. A chrysotile veinlet was seen to be replaced by talc and carbonate along its edges.

In close proximity to one of the small faults in F section, fibre of over 3 inches in length was found to be completely talcified. The asbestos was brittle and had completely lost its tensile strength. Under the microscope the country rock was seen to be composed of fine-grained talc and serpentine with isolated grains of carbonate. A vein of shorter fibre was noticed to be in the process of

being replaced by talc and carbonate.   The alteration
usually starts at the edges of the vein but may also begin
in the centre or along fractures (Plate 49).

2. THE CAROLINA ASBESTOS MINE ON THE FARM DIEPGEZET 33 AND
THE DEPOSIT ON ZILVERKOP 31 (See Appendix 8)

The occurrence of chrysotile on both the farms
Diepgezet 33 and on Zilverkop 31 has been described by
Hall (1930, p.146).

At the time of the author's visit to Diepgezet, the
mine was on the point of closing down and very little fibre
was seen underground.   The mine at Zilverkop was actually
closed and therefore inaccessible.

At Diepgezet the fibre horizon again occurs in the
serpentinized dolomite just above a basic sill.   The
horizon, however, is not the same as that worked on
Rietfontein, but lies much higher in succession - 15 to
20 feet below the Rooihoogte quartzite and shales of the
Pretoria Series.   The Zilverkop occurrence lies on the
same horizon about 1 mile to the south-east.   It is
understood that the best fibre at Diepgezet was obtained
at or near the surface and that with depth the fibre
deteriorated in quantity, but the quality remained good.
In August 1954 fourteen tons of handcobbed fibre was
produced of which nearly 50 percent was over 1 inch in
length.

In the deeper sections of the mine the same streaky
serpentinization as that of Rietfontein was noticed, but
no fibre.   In places the dolomite was highly contorted
but no actual faulting was seen.   On the northern sector
of the farm Diepgezet, however, a very conspicuous fault
was noticed.   The displacement on the Black Reef quartzites
can clearly be seen from the main Carolina - Barberton road.

3. BADPLAAS ASBESTOS MINE ON THE FARM GOEDVERWACHT 32

This occurrence has also been described by Hall (1930, p.151). In character it is similar to all the others and lies on the same horizon as Diepgezet and Zilverkop. Hall, however, does not mention the diabase dyke, along which a fault with downthrow on the south occurs. The displacement in the Rooihoogte quartzite is clearly seen directly above the mine. Mining has only been carried out on the north side of the dyke.

Intensive weathering of the diabase dyke at its contacts has given rise to the so-called "mud seams". The result is that in no instance has any of the mine workings penetrated the diabase dyke.

4. ELANDSHOEK ASBESTOS MINE NEAR MONTROSE FALLS

This occurrence differs from the others so far described in that the fibre occurs in serpentinized dolomite along a basic dyke instead of a sill. It is situated on the farm Elandshoek 139, about 5 miles due west of the confluence of the Elands and the Crocodile rivers and some distance south of the main road from Machadodorp to Nelspruit.

A near vertical basic dyke, varying in composition from diabase to pyroxenite, cuts through the dolomite in a north-south direction. The chrysotile asbestos deposits associated with this dyke are situated on the eastern side of a ridge running in a NNE - SSW direction. The maximum width of the dyke is about 95 - 100 feet. Higher up along the slope and towards the crest of an east-west spur the dyke decreases in width to a mere 30 feet (T.W. Gevers - unpublished report). Near the main workings a second dyke about 20 feet wide was noticed parallel to the main dyke. The two dykes are separated by about 30 feet of dolomite.

Serpentinization of the dolomite has taken place for several feet on either side of both dykes. The serpentinized dolomite is yellowish in colour and consists of irregular zones and patches which peter out away from the dyke. Professor Gevers also mentions bands of serpentinite parallel to the bedding of the dolomite.

Parallel seams of chrysotile asbestos have developed in this serpentinized dolomite parallel to the dyke contact. The best development of fibre is in the immediate contact zone and seems to peter out away from the dyke. At a few places veins of chrysotile also occur in the dyke itself (T.W. Gevers - unpublished report). At such localities the dyke appears to be composed entirely of ortho-pyroxene largely altered to serpentine.

Most of the fibre is less than $\frac{1}{2}$ an inch in length, although some seams of over $\frac{3}{4}$ inch were noticed. The percentage of fibre is very variable and in many places the asbestos peters out altogether. The best section observed contained over 10 separate seams totalling nearly 7 inches of fibre over a width of 18 inches. The quality of the fibre, however, cannot be compared with that from Diepgezet or Rietfontein. Although not brittle it is a much harsher fibre with lower tensile strength. On surface the fibre has been traced for several hundred feet along strike and in depth mining has proved it down to 50 feet. The fibre zone, however, appeared to pinch out downwards.

5. OTHER OCCURRENCES

Apart from the above mentioned occurrences, chrysotile asbestos is found at several other localities in the dolomite of which the following were visited by the author:

Normandale 280 and Sacramento Creek

These farms are situated about 15 miles north of the town of Pilgrim's Rest. The chrysotile seams occur in serpentinized dolomite just above a diabase sill and a small distance below the lowermost beds of the Pretoria Series. On Normandale a small mine was situated near the top of a densely wooded kloof and just above a high krantz formed by the diabase sill. A small fault runs through the mine and along the western side of the kloof. The fibre is restricted to the vicinity of the fault.

Graskop 27

On the Graskop Townlands, just south of the main Pilgrim's Rest – Graskop road and less than one mile north-east of the junction with the road to Sabie, chrysotile has been mined in the serpentinized dolomite just above a diabase sill (Fig.6) (see also Hall, 1930,p.222). The dolomite at the mine forms a krantz approximately 35 feet high and is then followed by the "Blyde Rivier quartzite" and bluish-black shales of the Dolomite Series. In a kloof, south of the one in which the fibre occurs, a diabase dyke with a north-south strike, can be seen.

The formation has been downfaulted on the east side of this dyke. The fibre in the mine was of extremely good quality and in places over $1\frac{1}{2}$ inches in length. It has been mined out up to the dyke, but because of faulting further development went through the dyke into the foot-wall sill and mining activities were stopped.

Fibre was also encountered above the diabase sill next to the dyke in the densely wooded kloof south of the mine. It was of inferior quality and not much prospecting has been carried out. Also on the western (upthrow) side of the dyke asbestos has been mined north of the Graskop-Pilgrim's Rest main road.

On the property of the Forestry Department about one

mile south of the mine the contact between the diabase sill and the overlying dolomite is again exposed.   This exposure is, however, about 500 feet west of the dyke and only very short fibre (less than $\frac{1}{4}$" in fibre length) was noticed in the serpentinized dolomite.

Olifantsgeraamte 459

This occurrence is situated some 4 to 5 miles west of Sabie on the property of the South African Forest Investments Limited.   The fibre again occurs in serpentinized dolomite just above a diabase sill.   The dolomite dips at a low angle to the west and, since the mine is situated on the eastern slope of a wide kloof running nearly north-south, the mine workings extended up dip.   Fibre of very good quality was extracted but petered out after a few hundred feet.

Chrysotile is also reported to occur on the farm Ceylon 218, adjoining Olifantsgeraamte to the north.

Appeldoorn 60

On the farm Groenkloof, a portion of Appeldoorn 60, which lies about 10 miles east of Carolina and just south of the main Carolina - Badplaas road, chrysotile asbestos of nearly an inch in fibre length has been found in prospecting pits.   The fibre occurs in thinly bedded dolomite, alternating with cherts, lying just above a thick diabase sill.   Higher up, the succession is obscured by sandstones of the Ecca Series of the Karroo System.   Although no Dwyka Tillite was noticed below the Ecca sediments, a small thickness must be present since glacial erratics of serpentinite and quartzite were found strewn over the countryside.

The fibre is associated with a well defined fault which strikes approximately north-south and has a down-throw of about 40 feet on the eastern side (Plate 15).

Unfortunately the depth of weathering is rather great and most of the fibre, although of fair length, is nearly completely decomposed. The fibre is also restricted to the immediate vicinity of the fault.

Kalkkloof 250

On the same farm as that on which the Kalkkloof Asbestos Mine is situated in serpentinite of the Jamestown Complex, prospecting has also been carried out for fibre in the dolomite. On the north side of the tributary of the Assegai Loop, which runs towards the western boundary of the farm, chrysotile asbestos occurs associated with a well exposed fault (Plate 12). The displacement is only about 6 feet but fibre is found for several tens of feet away from the fault. From the development carried out it would appear that the fibre development was better on the downthrow than on the upthrow side. Fibre up to 2 inches exists, but it is harsh with a low tensile strength.

Rietfontein 70, Portions A and B

Between the Congo-Vaal Mine, situated on Rietfontein 70, portions E and F, and Goedverwacht 32, which adjoins Rietfontein to the north, two small occurrences of chrysotile are found.

In both deposits the fibre occurs directly above a diabase sill but the fibre is of inferior quality. The occurrence on portion A is situated on a steep slope and due to lack of outcrops little of the structure could be seen. The other deposit occurs on the southern side of the spruit running along the boundary between portions A and B. The fibre here is restricted to the immediate vicinity of a small fault striking about east-west and possessing a throw of approximately 10 feet.

Engelschedraai 175 and Uitkomst 183

From the new Barberton map of the Geological Survey (1955) it can be seen that on the farms Engelschedraai 175

and Uitkomst 183, which lie approximately 10 miles due north of Badplaas, a diabase dyke accompanied by a fault cuts through the dolomite of the Transvaal System. Several diabase sills also occur in the dolomite and are intersected by the fault dyke.

From the investigation of the several asbestos deposits so far mentioned the author had observed a definite association of chrysotile asbestos and faulting or fault-dykes. It was then decided to visit the above mentioned farms and to inspect the areas where fibre could possibly exist.

On Uikomst, just north of the point where the fault-dyke cuts through the Gladde spruit, several adits were found exposing chrysotile asbestos up to $\frac{3}{4}$ inch in fibre length. Insufficient overburden has, however, permitted decomposition of the fibre at all places where it was opened up.

On the southern portion of Uitkomst, fibre up to 4 inches in length was also exposed above the upper diabase sill near the fault-dyke. Here, too, the fibre was completely decomposed by weathering. At the lower sill it was found that a chert zone in the dolomite followed on the diabase so that no serpentinization could take place.

On Engelschedraai, which adjoins Uitkomst to the south, the fault-dyke follows the eastern slope of a broad valley with the result that exposures are very poor. Brittle fibre, 1 inch in length, was, however, noticed at one locality close to the dyke. West of the main dyke another small dyke parallel to the main one can be seen. Chrysotile up to $\frac{3}{4}$ inch in length and of good quality was found above a diabase sill near this dyke.

IV   INVESTIGATION OF THE SERPENTINE MINERALS

A.   PREVIOUS WORK

The name Serpentine was first used by Discordides in Materia Medica in the year 50 A.D., and the name chrysotile for the fibrous variety was given by Franz von Knobel in the "Journal für Praktische Chemie", Vol.2, 1834.   In 1840 E. Schweizer described in "Pogg's Annalen für Physik und Chemie", Vol.49, a mineral to which he gave the name Antigorite.   The name Ferro-antigorite for the iron-rich variety was suggested by Harry von Eckerman in the Geol. For. Forh., Stockholm, Vol.47, 1925.   In the literature since then, nearly thirty different names have been given to different varieties and modifications of these minerals.

1.   G.C. Selfridge, 1936

Selfridge gives a comprehensive summary of all previous work done up to 1936.   In hand specimen the serpentine minerals can be classified into massive, lamellar and fibrous varieties.   A large number of specimens were studied optically and by means of X-rays.   Previous optical studies mentioned by him may very briefly be summarized as follows:

Winchell classifies antigorite with the chlorites but chrysotile is listed as a separate mineral.

Rogers and Kerr consider platy antigorite to be the main constituent of most serpentinites, with minor quantities of isotropic serpophite.   Chrysotile is a separate mineral.

Krotov states that antigorite and chrysotile are the same mineral with slightly different structures which grade into one another.

Graham also considers antigorite (massive serpentine) and chrysotile (fibrous serpentine) to differ in form but not in kind.   When the fibres become long enough to be seen with the naked eye, they are called chrysotile but when they are of microscopic size and unorientated they form antigorite.

Fisher describes the formation of antigorite from olivine and states that chrysotile is the fibrous form of antigorite.

Dolmage divides the serpentine-minerals into two varieties: platy antigorite and fibrous chrysotile.

Drasche describes the formation of bastite from
   pyroxene.

Bonney and Raisin came to the following conclusions:
   (i) That chrysotile and antigorite are dimorphous
        forms;
  (ii) Antigorite has a slightly greater refractive
        index than chrysotile;
 (iii) Pleochroism may be present but is not essential;
  (iv) There is no hard and fast rule as to when the
        fibrous and when the platy mineral will form;
   (v) Typical antigorite is formed under slight
        pressure.   When pressure is very great
        antigorite is not typical.

Tertsch finds two minerals, α and γ serpentine, in all
   serpentinites.

Angel and Martiny describe a mesh structure consisting
   of chrysotile, sometimes with cores of antigorite.

Angel studied various serpentine-minerals and divides
   them into several classes based mainly on structure.

Optical Properties

Selfridge determined the optical properties of a great

number of serpentine minerals using fragments and the

immersion method.

Average		
Refractive :	Serpentine (chrysotile)	1.538 - 1.570
Indices	Antigorite	1.555 - 1.580
Birefringence :	Serpentine (chrysotile)	0.007 - 0.008
	Antigorite	0.004 - 0.007

The 2V is small and both varieties are optically negative.

Since all optically negative chlorites have refractive

indices greater than 1.580, the serpentine minerals can

easily be distinguished from the chlorites.   In thin

section both varieties appear fibrous (even the antigorite

from the Antigoro Valley).   Antigorite has a faint tinge

of colour, but serpentine (chrysotile) is colourless.   No

pleochroism was noticed.   The textures consist of aggregates,

anhedral units, structureless fields, veins, mesh textures,

hour glass shapes, etc..   On page 497, Selfridge states

that in no instances were the two minerals found together.

In rock which contained veins of chrysotile, the matrix

was also serpentine (chrysotile) and not antigorite.

Chrysotile can form from serpentine by mere recrystallization

with only minor changes in the interplanar spacings.   If it had to form from antigorite major changes must take place.

Chemical analyses indicate that serpentine and antigorite are dimorphous forms with chemical formula $Mg_3Si_2O_5(OH)_4$. The magnesia and water may be slightly higher in serpentine than in antigorite, with difference in water content more marked than that of magnesia.   These differences in chemical composition may be the explanation of the higher refractive index of antigorite.

Selfridge concludes that only two serpentine minerals exist, namely serpentine and antigorite.   Chrysotile is the fibrous form of serpentine.   The name Serpentinite is suggested for a rock containing both minerals.

2.   F.V. Syromyatnikov, 1936

In the same year in which Selfridge's paper appeared, a new mineral, a structural variety of chrysotile, called Ishkyldite, was described by Syromyatnikov.   This mineral has the chemical formula $H_2OMg_{15}Si_{11}O_{47}$ and the following optical properties: $N_z = 1.573$, $N_x = 1.566$, $N_z - N_x = 0.007$, $2V = 58^o$.   The identity period in the direction of the fibre axis is $9.68Å$ and its S.G. = 2.62.

It is suggested that Ishkyldite forms at lower temperatures than chrysotile and that stress was probably present during its formation.

3.   J.W. Gruner, 1937

Gruner investigated the structure of the serpentine minerals.   He agrees with B.E. Warren and W.L. Bragg (1930), who described the structure of chrysotile as having a double chain like that of amphiboles.   Antigorite may have a chain-like or sheet-like structure.   Only two serpentine minerals exist - chrysotile and antigorite (ishkyldite excluded). When it is not possible to differentiate between them, the name serpentine should be used.

4. Endel Aruja, 1945

An X-ray study of the crystal structure of antigorite was carried out by Aruja in 1945. He considers antigorite as a dimorphous form of chrysotile with the chemical formula $Mg_3Si_2O_5(OH)_4$. He felt that the study of the antigorite structure might throw light on the structure of chrysotile. There are two main differences between these two structures:

a. The diffraction lines on the X-ray photographs of chrysotile are broad, while those of antigorite are sharp.

b. The a-axis of antigorite (43.4Å) is about eight times longer than the corresponding axis in chrysotile (5.3Å). Gruner had also found that chrysotile and antigorite structure were comparable in the c-direction.

The density of antigorite as calculated from the unit cell was found to be 2.51 gm/ccm. This value is 3.5% less than the observed density of 2.60 gm/ccm. Aruja considers the difference to be due possibly to isomorphous replacement by heavier atoms.

Comparing the intensities of the reflections in the two minerals a strong analogy was found - particularly the (00ℓ) and the $(0k0)$ reflections. Aruja thus suggests that antigorite must have the same sequence of atomic planes parallel to (001) as chrysotile which has the following sheet-like arrangement:

$$
\begin{array}{c}
6\ O \\
4\ Si \\
4\ O + 2(OH) \\
6\ Mg \\
6\ (OH)
\end{array}
$$
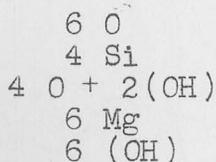
The thickness of one such layer is approximately 7.3Å (Fig.7A). In chrysotile the c-axis was taken as 14.6Å due to the presence of very weak (20ℓ) reflections. In antigorite these are either absent or lost in the background. Certain streaks were noticed parallel to the c-axis. These streaks may be due to "errors" in packing from sheet to sheet or every second sheet. The line-broadening of chrysotile is considered to be due to curved sheets.
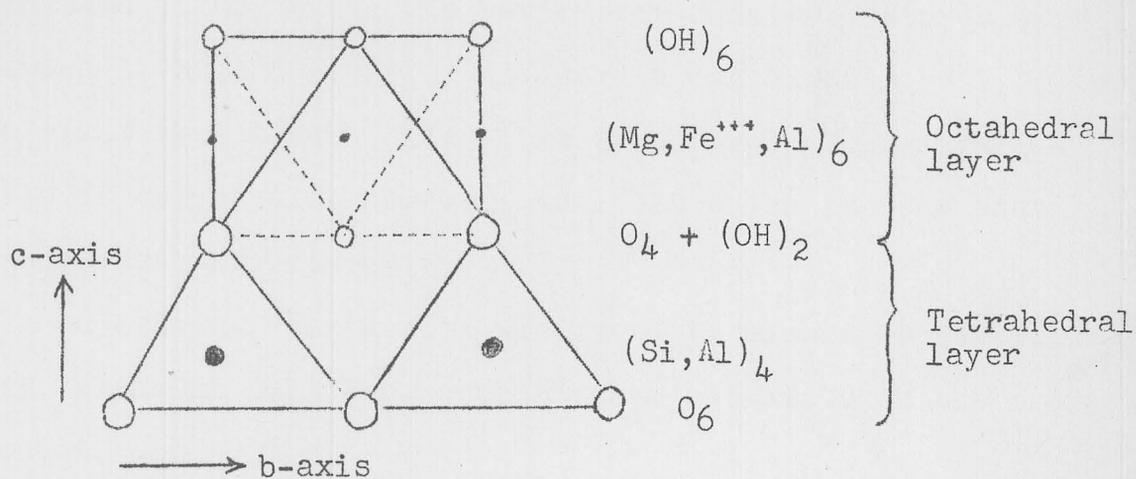
Schematic represetation of the layered structure of antigorite.

Fig.7 A

Rectified wave

Alternating wave

Zig-zag structure
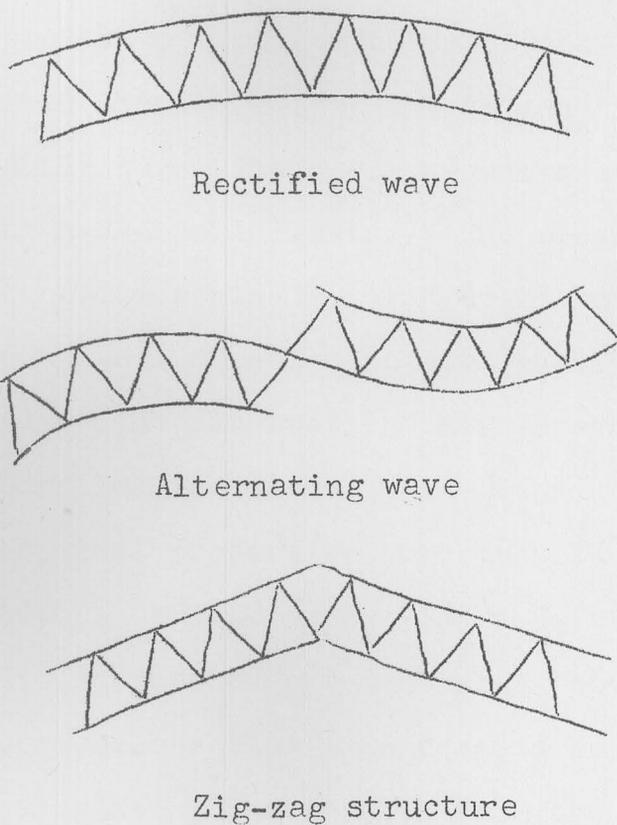
Trial structures for antigorite as suggested by Zussman(1954).

Fig.7 B

The axial ratios for chain-structures lie between 1.694 and 1.703, while the ratios for sheet-structures vary between 1.732 and 1.738. Antigorite has a ratio of 1.703 and might thus have a chain-like structure. The axial ratio of chrysotile, however, is 1.729 which is near that of the sheet structures.

On heating, antigorite was found to change to forsterite only, although Callière reported some enstatite in the end product.

5. Suzanne van Dyke Beatty, 1950

X-ray work done on various types of asbestos is discussed and it is found that the lines in the diffraction patterns of chrysotiles differ in sharpness, number and d-values. These variations are thought to be due to differences in crystallinity.

6. H.H. Hess, R.J. Smith and G. Dengo, 1952

A specimen of antigorite previously described by Dengo was examined chemically, by X-rays and by means of Differential Thermal Analysis. The specimen was massive, pale green in colour and had a dull lustre. The S.G. = 2.603 and the hardness on Mohs scale $3\frac{1}{2}$. Crystals were usually very small but a few up to 1 mm and elongated parallel to the a-axis were found. In thin section they showed a well developed parting parallel to (00l).

The optical properties were as follows: $N_z = 1.5670$, $N_y = 1.5660$, $N_x = 1.5615$, $N_z - N_x = 0.0055$ (all values ± 0.0005); dispersion r>V moderate; optic sign negative; $X \perp (00l)$, anomalous blue interference colours.

In calculating the formula from the chemical analysis the authors arrive at a formula which differs from that of normal serpentine, namely $Mg_7Si_5O_{13}(OH)_8$. In their calculations Al^{+++} is divided between the positions of Si^{++++} and Mg^{++} in the ratio of $15\frac{1}{2}$ to $4\frac{1}{2}$. (Why this is done is not quite clear).

The d-spacings for the mineral are given and also a D.T.A.-curve. A broad, shallow endothermal peak is present a little above $100^{\circ}C$ and a strong endothermal peak at $782^{\circ}C \pm 5^{\circ}C$. No exothermal peaks were observed.

In their investigation of the system $MgO-SiO_2-H_2O$, Bowen and Tuttle (1949) found only chrysotile and no antigorite. The stability range is thus not known. In the field, Smith has found serpentine (chrysotile) veins in sediments which have undergone regional metamorphism in the chlorite-biotite sub-facies of the greenschist facies. It is considered that antigorite needs a higher grade of metamorphism for its formation. In another area Smith found antigorite in metamorphic rocks of the albite-epidote amphibolite facies. The authors (Hess, et al.) thus come to the conclusion that chrysotile will change to antigorite at a temperature slightly higher than that of the greenschist facies and in the presence of shearing stress.

T.F. Bates and J.F. Mink (1950) expressed the opinion that chrysotile and antigorite were similar to endellite and kaolinite - tubes and plates. The Si-O layer would normally be too small to fit on the Mg-OH layer and curvature will take place. Antigorite usually contains more Al_2O_3 than chrysotile and a replacement of 4Al for 6Mg in small amounts may stabilize antigorite. Mg^{++} may also be replaced by Fe^{+++}.

Hess and his co-workers feel that, since olivine normally contains less Al_2O_3 than ortho-pyroxene, the former will change to chrysotile and the latter to antigorite (bastite). They also feel that, if the Mg : Si ratio of 7 : 5 is correct, the increase in Si relative to Mg might also explain the stability of antigorite plates.

7.   B. Nagy and T.F. Bates, 1952

These authors studied the stability of chrysotile compared with antigorite.   Using nitrogen, they determined that the surface areas of the two minerals were of similar order.   Chrysotile is found to have lower chemical as well as lower thermal stability than antigorite.   Since there is no significant difference in their surface areas the authors suggest tension in the tubular crystals as the explanation for the lower stability.   In the above mentioned work reference is also made to the following important papers:

> L. Pauling, 1930, predicted that there would not be a magnesium analogy of the kaolinite structure because of the difference in sizes of the octahedral and tetrahedral layers.   He also suggested that if serpentine had the kaolinite structure the sheets would tend to curve.

> B.E. Warren and K.W. Herring, 1941, examined the structure of chrysotile asbestos and came to the conclusion that it had the kaolinite layered structure.

> T.F. Bates, L.B. Sand and J.F. Mink, 1950, from electron microscopic studies decided that chrysotile asbestos consists of tubular crystals.

8.   J. Zussman, 1954

In this paper on the investigation of the crystal structure of antigorite, Zussman first gives a summary of the work of Selfridge (1936) and of Aruja (1944).   He then describes the morphology and the optics of the specimens used in the investigation.   The following optical properties were determined: $N_z = 1.564$, $N_y = 1.563$, $N_x = 1.560 \pm 0.001$, Na light $2V_x = 55^{\circ} \pm 2^{\circ}$, $r > V$ weak, $Z = b$ and X and Y are parallel to the c and a axes respectively. An equal quantity of another mineral with inclusions of iron ore was separated magnetically.   This mineral had a mean refractive index of 1.563 ± 0.002.   The two varieties had nearly similar X-ray patterns.

Zussman then discusses the curved sheet structure of chrysotile.   Aruja and Whittaker showed that chrysotile

had a layered structure. Pauling predicted that such a structure would tend to curve. Bates, Sand and Mink and also Noll and Kircher (1951, p.219) showed that the sheets were curved round the a-axis. Zussman investigated 13 specimens by means of fibre photographs and found that 8 had a repeat distance of $5.3Å$ and 5 had a repeat distance of $9.2Å$. He thus feels that curvature can take place along both the a- and the b-axes, and that preference for one axis over the other may depend more on the physical conditions during growth than on isomorphous replacements as suggested by Hess, Smith and Dengo, Nagy and R. Roy and D.M. Roy.

Possible structures for antigorite are then discussed. A single crystal diffraction pattern was compared with results obtained with a diffraction spectroscope and trial cardboard structures. Three possible structures are suggested - a rectified wave, an alternating wave, or a zig-zag structure (Fig.7B).

From a chemical analysis Zussman suggests the following stacking of layers for the antigorite structure:

$$
\begin{aligned}
&51 \ O \\
&34 \ Si \\
34 \ O \ &+ 15 \ (OH) \\
&48 \ Mg \\
&48 \ (OH)
\end{aligned}
$$
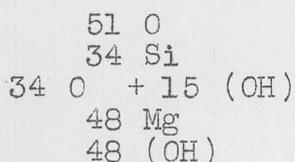
Finally in his conclusion he states that both the "alternating wave" structure with a radius of $65Å$ or the "rectified wave" structure with a radius of approximately $85Å$ are possible structures, but that the latter is more plausible structurally. The antigorite of Hess and his co-workers is considered to be essentially the same as ordinary antigorite. Brindley (1954) also recalculated the formula of the Venezuela antigorite (described by Hess and collaborators) and finds it to fit well with normal antigorite.

9. G.W. Brindley and O. von Knorring, 1954

In this paper the chemical formulae of two specimens
of vein serpentinite from Unst, Shetland Islands, are
investigated. For antigorite (a), a structural formula
based on 9(O+OH) atoms is given. All the Al^{+++} and some
Fe^{+++} ions are grouped with Si^{++++} to fill the tetrahedral
positions and Mn, Fe^{++} and the remaining Fe^{+++} are placed
in octahedral positions with Mg. Only 2.937 ions are
however available for these positions.

The structural formula for antigorite (b), based on
the same grouping, is not satisfactory at all. The
formula is then recalculated on the basis of Si = 2 which
is more consistent with the general procedure of first
filling the tetrahedral positions. The following result
is obtained:

Serpentine   Brucite

$$(Mg_{2.716}Mn_{0.002}Al_{0.006}Fe'''_{0.134}) \; Si_{2.00} \; (O_{4.857} {}^{+}OH_{4.143}) \div Mg(OH)_2$$

| 2.858 atoms | 2 atoms | 9 atoms | 0.537 atoms |
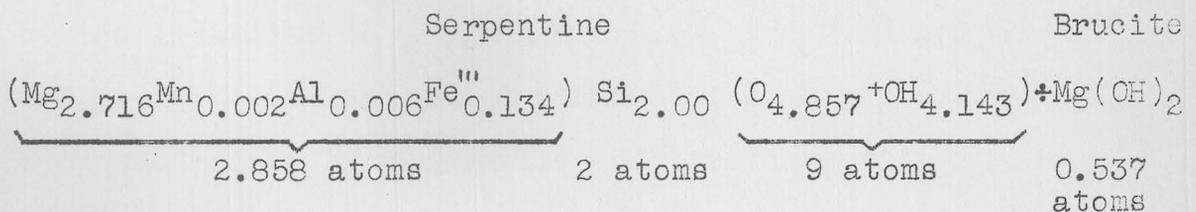
(Although it is stated that no indication of brucite was
found in either the X-ray or the D.T.A.-work, the D.T.A.-
curve for antigorite given shows a small endothermic peak
at $430^{\circ}C$, which corresponds with the brucite-peak).

10. J. Zussman, 1956

Brindley suggested a unit cell for antigorite with
dimensions a = 5.322, b = 9.219 and c = 14.53. There are,
however, also some lines which correspond with a repeat
distance of 43.8Å. This "super-lattice" parameter is
explained by Onsager (1952) as due to an undulating sheet
structure, but Zussman feels that it could be due to the
superposition of two serpentine minerals - one with a
small unit cell and the other with a large cell.

As far as the structural formula goes, Zussman does
not agree with the calculations of Brindley and von Knorring.

He states that, unless the weight of the unit cell content is known, a variety of structures can be suggested.

11. E.J.W. Whittaker and J. Zussman, 1956

These authors present methods for identification of the serpentine minerals by means of X-rays. They consider the methods of Selfridge to be unreliable and suggest new techniques. Two varieties of chrysotile are recognised – ortho-chrysotile with unit cell dimensions a = 5.34Å, b = 9.2Å and c = 14.63Å and β = 90° (orthorhombic), and clino-chrysotile with a = 5.34Å, b = 9.2Å, c = 14.65Å and β = 93°16' (monoclinic). Both these varieties have two-layer structures and replace the four varieties with mono-layer structures as suggested by Jagodinski and Kunze. A variety with similar cell dimensions but a fibre axis of 9.2Å is called para-chrysotile. A third distinct mineral called lizardite (a = 5.3Å, b = 9.2Å, c = 7.3Å and β = 90°) was found. It was also determined that bastite was composed mainly of chrysotile and lizardite rather than antigorite and that ortho-antigorite was probably ortho-chrysotile.

The ratio of ortho- to clino-chrysotile in different specimens varied within wide limits. Many specimens were found to consist of pure clino-chrysotile but only one specimen consisted of the pure ortho-variety. Other specimens varied from nearly pure clino-chrysotile to 81% ortho-chrysotile. (Thetford 7% and Shabani 35% ortho-chrysotile). It was also determined that Thetford specimens contained 3% and Rhodesian and South African specimens 0 – 10% of para-chrysotile. The reason for the presence of either ortho- or clino-chrysotile is not certain, but it might be due to energy differences during nucleation.

To distinguish between chrysotile and antigorite the intensity relationships, the presence of extra lines and

small differences in corresponding lines in X-ray diffraction powder photographs should be studied. The strong antigorite line 2.52Å may be confused with the 202 line of lizardite but the latter is never greater than 2.50Å. The antigorite line 1.563Å is important in that it has no counterpart in either chrysotile or lizardite. With the 1.541Å line it forms a pair which is somewhat similar to the lizardite pair, 1.535Å and 1.503Å. The lines of antigorite are usually sharper than those of the other serpentine minerals.

The following classification of the serpentine minerals is suggested:

$$
\text{Serpentine}
\begin{cases}
\text{chrysotile}
\begin{cases}
\text{clino-chrysotile} \\
\text{ortho-chrysotile} \\
\text{para-chrysotile}
\end{cases} \\
\text{lizardite} \\
\text{antigorite}
\end{cases}
$$

12. B. Nagy and G.T. Faust, 1956

In this paper the following classification for the serpentine minerals is suggested:

		Chrysotile-group	Antigorite-group
General Formula	: $Mg_6Si_4O_{10}(OH)_8$	chrysotile	antigorite
Hypo-thetical End Members	$\begin{cases} Fe_6Si_4O_{10}(OH)_8 \\ Ni_6Si_4O_{10}(OH)_8 \\ Mn_6Si_4O_{10}(OH)_8 \end{cases}$	ferro-chrysotile nickel-chrysotile manganese-chrysotile	ferro-antigorite nickel-antigorite manganese-antigorite

From chemical analyses Al, Fe^{+++}, Cr and Ca, Ti, Co, Cu and Na are also found in small quantities. Their presence may however be due to impurities.

A detailed account of previous mineralogical and structural work on the serpentine minerals is given and in a further chapter previous chemical-geological studies are discussed. This may be summarized as follows: The first attempt to synthesize the serpentine group of minerals was made by Mouromtseff (1927). Van Nieuwenburg and Blumendal (1930) reported a synthetic product which was probably

serpentine.   Jander and Wuhrer (1938) and Jander and Fett
(1939) obtained serpentine and talc from a charge of MgO,
SiO_2 and H_2O.   An attempt to synthesize antigorite by
adding alkalies to the starting mixture was made by Strese
and Hofmann (1941).   None of these products was definitely
identified.

Noll (1944) was the first to study the end products
under the electron microscope.   He observed short fibres
about 1μ long.   When KOH was added flakes were formed
instead of fibres, but both had the properties of chrysotile.
Epprecht (1947) also suggested that KOH may aid the formation
of antigorite.   In 1951 Balduzzi, Epprecht and Niggli tried
to lengthen fibres artificially.   They reported some success,
but it could not be done on an economic scale.

Bowen and Tuttle (1949) studied the system $MgO-SiO_2-H_2O$
and found chrysotile stable at temperatures below $510^{o}\pm10^{o}C$
and pressures from 2,000 to 40,000 psi.   They were unable
to synthesize antigorite.   Yoder found with his study of
the $MgO-Al_2O-SiO_2-H_2O$ system that flaky aluminous serpentine
forms below $520^{o}C$ and a pressure of 2,000 to 30,000 psi.
The properties of this substance were, hoever, different
from normal antigorite.

The authors then suggest that field relationships may
solve the problem.   Sobolev (1945) noted that chrysotile
may recrystallize into antigorite.   Hess, Smith and Dengo
(1952) described antigorite derived from chrysotile under
dynamo-thermal metamorphism.   Nagy (1953) suggested that
the recrystallization of chrysotile into antigorite was
probably more common than generally thought.

After studying a large number of specimens the authors
confirmed the results of Selfridge, namely that only two
serpentine minerals exist, chrysotile and antigorite and
that all other serpentinites are mixtures of these two end
members.   The difference between the properties of chrysotile
and antigorite may be tabulated as follows:

	Chrysotile	Antigorite
1. Electron Microscope Morphology	Tubular fibres	Flakes or laths
2. R.I. Range	1.53 - 1.56	1.56 - 1.58
3. X-ray Diffraction	See the results of Whittaker & Zussman (1956)	
4. Chemical Composition	$Mg_6Si_4O_{10}(OH)_8$ with 2.9 - 1.9% Fe_2O_3 or Al_2O_3	$Mg_6Si_4O_{10}(OH)_8$ with 6.5 - 2.9% Fe_2O_3 or Al_2O_3
5. HCl	Treatment with one normal HCl results in structural collapse	Treatment with concentrated HCl results in structural collapse
6. Electron Beam	Disintegrates rapidly	Does not affect.

Differential Thermal Analyses were also done by Nagy
and Faust and four curves of antigorite, chrysotile and
mixtures of the two are presented.

They all have strong endothermic peaks between $670^{\circ}C$
and $802^{\circ}C$ and show exothermic peaks of varying intensity
between $805^{\circ}C$ and $872^{\circ}C$. The disintegration temperatures
for antigorite appear to be greater than those of chrysotile.

Finally the authors suggest a semiquantitative method
for determining the percentage antigorite-chrysotile present
in any mixture. Chrysotile and antigorite have more or less
the same (00ℓ) reflections. HCl decomposes chrysotile more
rapidly than antigorite. The intensity of the (00ℓ)
reflection decreases accordingly and presents basis for
determining the percentages present. In their experiments
the authors found an error of ±8% antigorite. They
conclude that all serpentinites are natural mixtures of the
two end members, chrysotile and antigorite, and should be
defined as percentages of these end members.

B.   PRESENT STUDIES

General

Over two hundred and fifty specimens of serpentinite, chrysotile and associated rock types were collected from the various mines visited.   Nearly all of these were examined in thin section and the thirteen specimens listed below were eventually chosen for detailed examination:

V.14: Dark green, fine-grained serpentinite from the hangingwall of the Havelock ore-body.   The specimen was taken in the drainage adit from 3rd Level, about 30 feet north of the hangingwall sill.

V.22a: Light green, granular serpentinite which contains veins of chrysotile asbestos up to $\frac{3}{4}$ inch in length. This specimen represents the rock which forms the main ore-body of the Havelock Asbestos Mine.   It was taken in the winze from 3rd Level to the drainage adit.

V.22b: Chrysotile asbestos occurring in light green serpentinite V.22a.   The fibre is of good quality with high tensile strength and a length up to $\frac{3}{4}$ inch.   The colour of the fibre is also light green and the fibre has a slightly talcy feel.

V.119: Dense apple-green serpentine (picrolite) occurring as a vein about 1 inch in width in light green serpentinite.   The specimen itself showed no signs of a fibrous structure but a few inches away a faint lineation perpendicular to the walls of the vein was noticed.   Still further away the serpentine graded into chrysotile asbestos.   The specimen was taken from the Drive East on the 4th Level, Havelock Asbestos Mine.

V.123: Chrysotile asbestos occurring in darkish green, coarse-grained serpentinite.   The chrysotile also

has a bluish-green colour and was of brittle and
springy quality, about $\frac{5}{8}$ inch in length.   The
specimen comes from near the 14E Surface Raise on
3B Level, Havelock Asbestos Mine.

V.126: "Pseudo"-fibre occurring in light green, dense
serpentinite.   Although the material has a fibrous
structure in hand specimen, it can not be separated
into individual fibres.   It has a whitish green
colour and has a talcy feel.   The specimen comes
from the crosscut west of the 14E Surface Raise on
3B Level, Havelock Asbestos Mine.

V.168: Brown serpentinized dolomite associated with
good quality fibre from the Congo-Vaal Asbestos
Mine, on the farm Rietfontein 70, Carolina district.

V.177: Dense, dark green serpentinite from the core of
a "boulder" occurring in the Sub D section of the
Hill Top Quarry at the Stolzburg Asbestos Mine.

V.178a: Dense, lighter green serpentinite occurring as
a shell around the dark green serpentinite V.177.
Chrysotile asbestos up to $\frac{1}{2}$ an inch in length also
occurs as concentric seams in this serpentinite.
Obtained from a "boulder" in the Sub D section of
the Hill Top Quarry, Stolzburg Asbestos Mine.

V.178b: Chrysotile asbestos, $\frac{1}{2}$ inch in length and
greenish in colour, occurring as concentric seams
in the serpentinite V.178a.   Sub D section, Hill
Top Quarry, Stolzburg Asbestos Mine.

V.198: Apple-green sheared serpentine occurring along
a shear plane in the Sunnyside Asbestos Mine.

V.211: Chrysotile asbestos, 6 inches in length and of
high quality but with a slightly talcy feel.   This

fibre was obtained from the 6th Level Drive of
the Amianthus Mine, just south of the 6th Level
adit.

V.231: Resinous serpentinized dolomite from Heynecke's
Asbestos Mine near Graskop.   This serpentine is
intimately associated with high quality asbestos.

Microscopic Description

Antigorite and chrysotile

In the hand specimen it is easy to distinguish
between veins of chrysotile and massive serpentinite.
When examined under the microscope large veins of
chrysotile are also readily recognised.   Massive
serpentinite, however, appears in a great variety of
forms.   It may consist of isotropic material with
birefringent veinlets surrounding or transgressing it;
it may be fibrous, unorientated, or may form a cross-
hatched or felted pattern;   it may occur in tufts or in
concentric bands.   In other cases the serpentinite
consists of a structureless field of material with a low
birefringence, sometimes with anomalous blue interference
colours.   Often it is quite impossible to predict the
type of serpentine from the hand specimen and it would
also appear as if one type of texture may change into
another.

From the summary of previous work done on the
mineralogy of the serpentine minerals it will be seen
that except for a few minor variations, two main minerals
are considered to exist: antigorite and chrysotile.
Work done by Nagy and Faust (1956) and an investigation
with the electron microscope carried out independantly
by the author have shown that many massive serpentinites
consist of an intimate mixture of these two minerals.

An attempt has been made to distinguish between antigorite and chrysotile by means of their optical properties (Selfridge, 1936). Chrysotile has slightly lower refractive indices but the birefringence is somewhat stronger than that of antigorite. The latter may also have a faint tinge of yellow but is non-pleochroic.

The author has found that some specimens (e.g. V.22a) consisted of concentric rings of colourless and yellowish material (Plates 22A and B, 23). The latter has slightly higher refractive indices than the colourless mineral but also shows somewhat stronger birefringence. Under the electron microscope it was found that all the minerals in the specimen were fibrous. Specimen V.119, which is isotropic in thin section, turned out to be fibrous under the electron microscope while specimen V.231, which is also isotropic, was shown to be flaky.

Seams of chrysotile are easily recognized under the microscope. Antigorite, on the other hand, even though it has a flaky habit, appears fibrous in thin section and resembles finely fibrous chrysotile. When the two minerals occur together as an aggregate it is therefore impossible to distinguish between them by means of the microscope. When it is not possible to distinguish the individual minerals the author would like to suggest that the term serpentine be used (Selfridge used serpentine for chrysotile only), and only when it has been established that the mineral is flaky should the name antigorite be applied. A rock consisting of both minerals should be called serpentinite, in the same way as a rock which consists of pyroxene is called a pyroxenite.

Ore minerals of serpentinite

All the serpentinites examined contained a small amount of ore minerals which occur as stringers, veinlets, irregular aggregates and as well-defined grains or octahedral crystals. The veinlets, stringers and

aggregates were found to be magnetite but the crystals were not so easily identified.   They all have opaque rims with reddish-brown, translucent centres and in some cases the very centre of the crystal was also opaque.   Many of the crystals are only represented by a "skeleton" of the original, i.e. the translucent portion has been replaced by transparent, isotropic material and only the thin opaque borders (and sometimes centres) remain (Plate 29).   In a few grains only partial replacement has taken place.

To identify the reddish-brown translucent mineral all the ore from specimen V.22a was separated by means of bromoform.   It was found, however, that all the ore was magnetic which would indicate to the author that the opaque rims of the reddish-brown mineral must also be magnetite.   An X-ray determination, carried out by Mr J. Ortlepp of the Government Metallurgical Laboratories, indicated the presence of chromite, and a spectrographical analysis done by Dr W.R. Liebenberg of the same laboratory showed the following composition:

$$
\begin{array}{lll}
\text{Fe} & & \text{large amount} \\[4pt]
\left.\begin{array}{l}\text{Ca}\\\text{Si}\\\text{Mg}\\\text{Al}\\\text{Cr}\end{array}\right\} & & \text{small amounts} \\[4pt]
\left.\begin{array}{l}\text{Ti}\\\text{Ni}\end{array}\right\} & & \text{traces}
\end{array}
$$

The presence of Ca is rather puzzling since no carbonate or any other Ca-bearing mineral was noticed in the specimen.   The Si and Mg probably come from serpentine impurity.   It is also possible that the isotropic mineral replacing the reddish-brown mineral is serpentine.   The important fact, however, is the relatively large quantity of Al and Cr.   This would indicate that the translucent mineral is not pure chromite but a member of the spinel-series, probably somewhere between chrome-hercynite and chrome-spinel.

Chrysotile asbestos was seen to contain thin needle-like inclusions of magnetite (Plate 33) but the spinel mineral was not noticed in any of the specimens.

Microscopic description of specimens on which further examination was carried out

V.14: This rock consists mainly of serpentine in the form of thin branching veinlets, slightly yellow in colour, surrounding colourless cores (Plate 20).   The cores have weak birefringence, the interference colours being first order grey and white.   The veinlets have a slightly stronger birefringence and a somewhat higher refractive index.   A small amount of talc and chlorite is present interstitially.   The latter can be distinguished from the serpentine by its anomalous blue interference colour. Ore in the form of grains is found disseminated through the rock.   Many of them are translucent red in the centre with opaque borders.   Some show a peculiar structure where the dark core is separated from the thin opaque rim by a ring of transparent material (Plate 29).   The ore is probably a member of the chromite - spinel series.

V.22a: In thin section this rock is seen also to consist of colourless cores of serpentine surrounded by yellowish veinlets.   These cores, however, are composed of fibrous serpentine orientated in three directions at 120° to one another.   The result is a crosshatched appearance (Plates 17 and 18).   A fair amount of brucite is present in the rock, usually occupying the centre of the cores and surrounded by veinlets of serpentine.   Some veins of brucite were also noticed.   Interstitially a few very small flakes of a mineral which may be talc could be seen. Ore is sparingly present in the form of stringers of magnetite and isolated grains of the chromite - spinel series.   The ore is often concentrated in and around the brucite.

V.22b: Under the microscope the asbestos is seen to consist of extremely fine fibres of chrysotile arranged parallel to one another. Small needles of magnetite occur locally in parallel intergrowths with fibre (Plate 33).

V.119: In thin section this specimen is seen to be composed of clear, colourless serpentine which is near-isotropic. On the edge of the specimen where it adjoins the country rock a faint banded structure with fine fibres can be noticed. Thin fractures, filled with birefringent material also occur. Magnetite in large euhedral crystals is found in the specimen (Plate 34).

V.123: This brittle fibre is seen in thin section to be composed of parallel fibres of chrysotile. At several places the fibre is in the process of being replaced by carbonate (magnesite). Thin zones of isotropic material were also noticed parallel to the fibres. No difference could however be found microscopically between the unaffected fibre of this specimen and normal good quality chrysotile.

V.126: This fibre is seen under the microscope to consist of long prismatic crystals of serpentine orientated perpendicular to the walls of the vein. Serpentine in the form of little tufts and radiating bundles occur throughout the section cutting across the longer crystals. Dolomite grains are present in zones parallel to the longer fibres. No ore was noticed in the specimen (Plate 30).

V.168: An extremely fine-grained rock consisting of calcite grains in a groundmass of serpentine. Finely divided hematite is disseminated evenly throughout the specimen giving the rock a brown colour in hand specimen.

V.177: In thin section this rock is fine-grained and seen to be composed of oval grains consisting of vein and core

type serpentine lying in a matrix of larger structureless
patches of serpentine. The cores are also non-fibrous
and near-isotropic. The veinlets in the different grains
are all orientated in the same direction. Ore in the form
of octahedra and as "skeleton" crystals (only a rim of
opaque material with a colourless transparent core), as well
as veinlets of magnetite occur. Radiating from the oval
grains are fractures often seen around olivine (Plate 40).

V.178a: This rock is seen to be composed of anhedral grains
of fibrous, crosshatched type of serpentine. No veinlets
were observed. Interstitially a small amount of chlorite
and some isotropic serpentine occurs. Ore is also present
as octahedra and in skeleton crystals but in smaller
quantities than in V.177 (Plates 38 and 39).

V.178b: This fibre is very similar to specimen V.22b except
that more magnetite needles are found included in the fibre
(Plate 39).

V.198: This rock shows a banded structure with alternating
zones of isotropic and weakly birefringent serpentine. Thin
crossfibre veins occur parallel to the banding in places.
A fibrous structure perpendicular to the banding was also
noticed (Plate 37).

V.211: Due to its soft nature it was extremely difficult
to prepare an undisturbed thin section of this fibre.
It would appear, though, that there are no impurities
and that the fibre is very easily separated into individual
fibres.

V.231: An extremely fine-grained rock consisting of near
isotropic serpentine with patches of weakly birefringent
material with anomalous blue interference colours. No
impurities were noticed.

Chemical Analyses

Nine specimens of serpentinite and chrysotile were selected for chemical analysis the results of which are given in Table I. It will be noted that the composition of all the specimens varies within narrow limits, except for specimen V.168, which has a very low silica and a high alumina, lime and CO_2 content. This specimen has therefore not be included in further calculations.

In Table 1 the compositions of the specimens are in weight percentages. Barth (1955) suggested that chemical analyses should be presented as ionic percentages rather than in weight percentages. The author strongly supports this suggestion, firstly because it greatly facilitates mineral norm calculations and, secondly, because most silicate structures are essentially ionic, rather than built up of oxides. Minerals of any composition can then be easily calculated directly from the chemical analysis and isomorphous replacements can be illustrated very clearly. The weight percentages recalculated to ionic percentages are given in Table II. To facilitate comparison with examples in the literature, however, weight percentages have been retained in the discussion on variations in composition and the ionic percentages are only used in the mineral calculations.

From Table I it can be seen that the main constituents of both the serpentinites and of chrysotile are silica, magnesia and water with small quantities of alumina and ferric iron, while most of the other elements are present only in very small amounts.

In the eight analyses presented the silica content varies from 33.82% to 41.70%, the magnesia from 37.13% to 44.49%, the alumina from 0.04% to 3.52%, the ferric iron from 1.92% to 10.46% and the water from 11.74% to 15.05%. It is interesting to note that, generally

Lab. No.	V.14	V.22a	V.22b	V.119	V.123	V.177	V.178a	V.178b	V.168
Nature in hand specimen	Massive	Massive	Fibrous	Massive	Fibrous	Massive	Massive	Fibrous	Massive
Nature under Electron Microscope	Fibrous & Flaky	Fibrous	Fibrous	Fibrous	Fibrous	Flaky	Flaky	(Fibrous)	–
SiO_2	36·91	33·82	39·96	34·99	39·35	36·36	38·41	41·70	28·22
Al_2O_3	3·52	1·57	0·85	2·50	0·04	2·37	2·79	0·82	9·98
Fe_2O_3	6·87	3·91	3·67	10·46	2·79	9·66	4·79	1·92	1·14
FeO	0·14	0·07	0·07	1·58	1·36	0·57	0·14	0·00	0·36
MgO	39·07	44·49	40·66	37·13	38·80	37·33	40·05	40·41	32·00
CaO	0·36	0·10	0·24	0·54	1·26	0·10	0·12	0·12	8·58
Na_2O	0·15	0·15	0·30	0·16	0·20	0·10	0·28	0·62	0·06
K_2O	0·12	0·12	0·12	0·12	0·18	0·10	0·15	0·22	0·08
$-H_2O$	0·34	0·47	0·79	0·28	0·40	0·88	0·57	1·01	0·53
$+H_2O$	12·66	15·05	12·67	11·74	11·76	12·38	13·01	13·47	11·15
TiO_2	0·05	0·08	0·08	0·05	0·10	0·05	0·06	0·04	0·52
P_2O_5	0·08	0·06	0·06	0·03	0·06	0·04	0·04	0·02	0·05
MnO	0·09	0·05	0·06	0·04	0·03	0·06	0·06	0·06	0·43
CO_2	0·18	0·11	0·13	0·28	3·52	0·13	0·13	0·10	6·84
TOTAL	100·54	100·05	99·66	99·90	99·85	100·13	100·60	100·51	100·24

TABLE I. CHEMICAL ANALYSES OF THE SERPENTINE MINERALS

Lab. No.	V.14	V.22a	V.22b	V.119	V.123	V.177	V.178a	V.178b
Si	12·49	11·35	13·52	12·16	13·16	12·61	12·91	13·92
Al	1·41	0·62	0·34	1·02	0·01	0·84	1·10	0·32
Fe'''	1·75	0·99	0·93	2·74	0·70	2·52	1·21	0·48
Fe''	0·04	0·02	0·02	0·46	0·38	0·16	0·04	0·00
Mg	19·70	22·24	20·50	19·22	19·33	19·29	20·04	20·09
Ca	0·13	0·04	0·09	0·20	0·45	0·04	0·04	0·04
Na	0·10	0·10	0·20	0·11	0·13	0·07	0·18	0·40
K	0·05	0·05	0·05	0·05	0·08	0·04	0·06	0·09
Ti	0·01	0·02	0·02	0·01	0·03	0·01	0·01	0·01
P	0·02	0·02	0·02	0·01	0·02	0·01	0·01	0·01
Mn	0·03	0·01	0·02	0·01	0·01	0·02	0·02	0·02
C	0·08	0·05	0·06	0·13	1·61	0·06	0·06	0·05
O + OH	64·21	64·50	64·23	63·86	64·10	64·32	64·30	64·59
TOTAL	100·00	100·01	100·00	99·98	100·01	99·99	99·98	100·02

TABLE II.   IONIC PERCENTAGES OF THE SERPENTINE MINERALS.

speaking, the non-fibrous specimens V.14, V.22a, V.119, V.177 and V.178a have higher percentages of both alumina and ferric iron than the fibrous specimens V.22b, V.123 and V.178b. The difference in alumina is particularly noticeable.

Care should be taken before arriving at conclusions, however, since many of the differences may be explained by the presence of impurities. A high magnesia content may be due to the admixture of brucite or magnesite. A small amount of talc would cause an increase in the silica and a lowering of the water content. Relatively high alumina may be due to the presence of chlorite or perhaps spinel. A high iron content could be due to magnetite impurity and the presence of calcium is probably due to small amounts of calcite or dolomite.

The relatively high percentage of alumina in the massive serpentinites can be partly explained by the presence of the spinel-mineral which was noticed in thin section. Comparing the amount of the latter mineral with the percentage alumina, however, the author feels that insufficient spinel exists to explain all the alumina. Very little chlorite was noticed in thin section and it is thus possible that a certain amount of Al^{+++} may occur in the serpentine as an isomorphous replacement of Si^{++++}. Since a serial relationship exists between Al/Si and Fe/Mg (Fig.8) and also between Al^{+++} and Fe^{+++} (Fig.9), it would seem possible that Fe and Al could occur as isomorphous replacements of Mg and Si respectively. Unfortunately the presence of impurities makes it impossible to prove this relationship. If it does happen, though, it would lend some support to the suggestion made by Bates and Mink (1950) that a replacement of the Mg by Al and Fe^{+++} would release the strain in the antigorite structure and so prevent curvature of the sheets. The replacement of Mg by Al and Fe as put forward by Bates and Mink has been
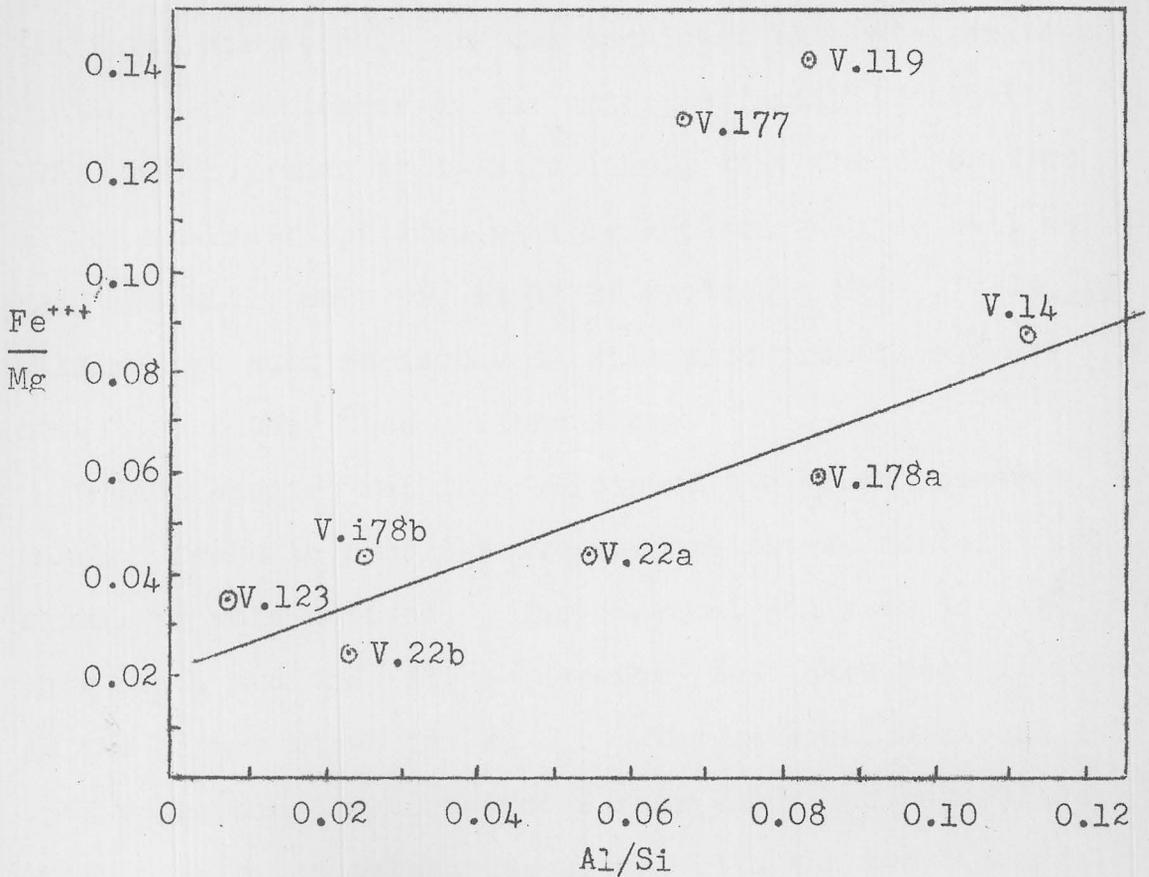
Graph showing the relationship between Fe^{+++}/Mg and
Al/Si in the serpentine minerals. Both specimens
V.119 and V.177 contain a high percentage Magnetite
which would explain their high Fe/Mg ratio.

Fig.8
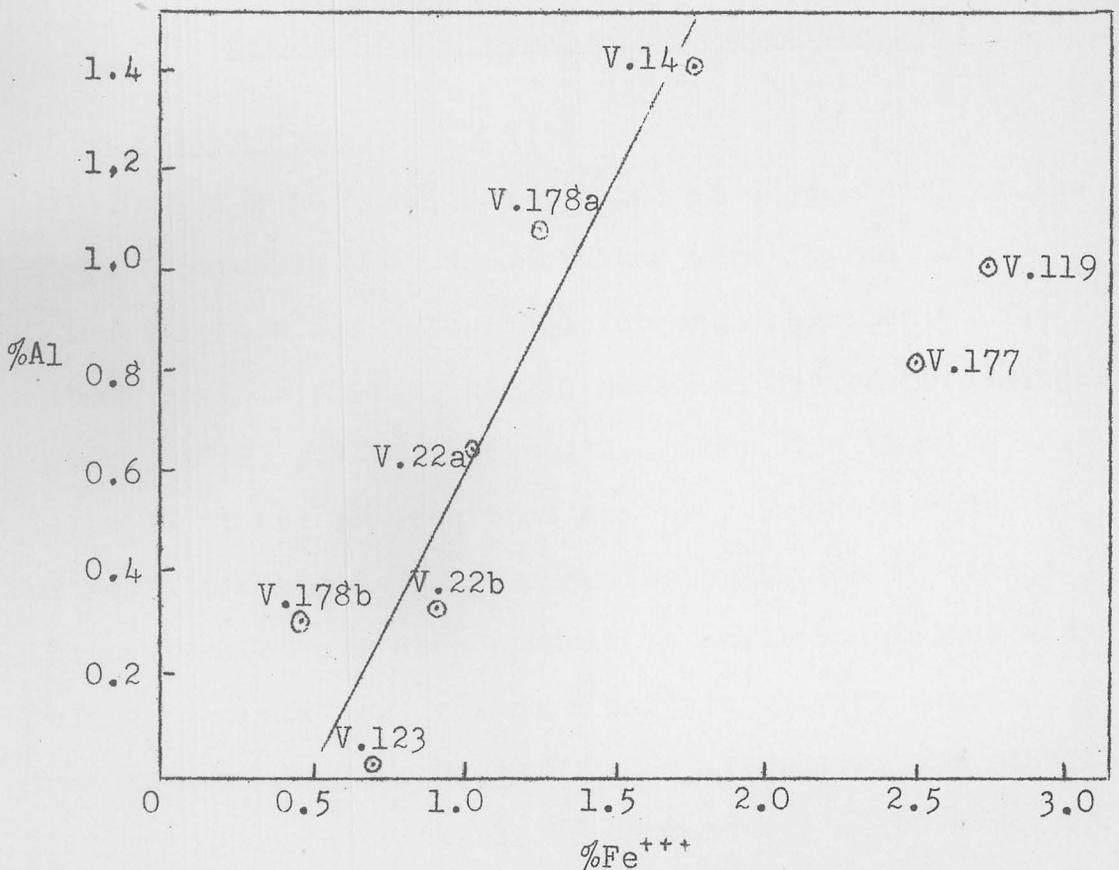
Graph showing the relationship between the percentage
Al and Fe^{+++} in the serpentine minerals. The presence
of magnetite impurity would explain the high Fe
content of specimens V.119 and V.177.

Fig.9

based on the analogy of the antigorite structure with the kaolinite structure. If one considers pure antigorite to be the Al-free member of the chlorite family (Winchell, 1951, p.381), then it is more likely that the Al present in the analysed specimen will be replacing Si as well as Mg. Fe will, however, still be replacing Mg. It is likely that such replacements will also promote a flaky structure rather than a fibrous one.

In a spectrographic analysis of the brown accessory mineral found in some massive serpentinites, chromium and aluminium were noticed. The chemical analyses do not show Cr_2O_3 and the latter therefore must have been included in the figure given for Fe_2O_3. The material analysed spectrographically contained a fair amount of magnetite which occurs intimately associated with the brown mineral. It was therefore impossible to determine the percentage Cr_2O_3 in the mineral nor the amount of Al_2O_3 associated with it.

Calculations based on chemical analyses

a) Molecular Norm

To get some idea of the original composition of the rocks from which the serpentinites were formed the Molecular Norm was calculated for each specimen. The method used is that of Niggli based on cation percentages (Barth, 1952, p.76) - Table III. From the results in Table IV it can be seen that apatite, ilmenite and orthoclase occur as small amounts in all the specimens. The carbonates are also present in small quantities and vary in composition from pure calcite to very nearly pure magnesite. Specimen V.123 differs from the others in that it contains nearly 9% carbonate. Albite occurs from a mere trace up to 3.25% in specimen V.178b which had a rather high sodium content. In specimen V.123

Lab. No.	V.14	V.22a	V.22b	V.119	V.123	V.177	V.178a	V.178b
Si	34·88	31·96	37·81	33·66	36·66	35·35	36·15	39·29
Al	3·92	1·75	0·95	2·83	0·04	2·36	3·09	0·91
Fe'''	4·89	2·78	2·61	7·59	1·95	7·06	3·39	1·36
Fe''	0·11	0·06	0·06	1·27	1·06	0·46	0·11	0·00
Mg	55·01	62·63	57·31	53·20	53·84	54·06	56·15	56·72
Ca	0·36	0·10	0·24	0·56	1·26	0·10	0·12	0·12
Na	0·27	0·27	0·55	0·30	0·36	0·19	0·51	1·13
K	0·14	0·14	0·14	0·15	0·21	0·12	0·18	0·26
Ti	0·04	0·06	0·06	0·04	0·07	0·04	0·04	0·03
P	0·06	0·05	0·05	0·02	0·05	0·03	0·03	0·02
Mn	0·07	0·04	0·05	0·03	0·02	0·05	0·05	0·05
C	0·23	0·14	0·18	0·37	4·47	0·17	0·17	0·13
TOTAL	99·98	99·98	100·01	100·00	99·99	99·99	99·99	100·02
O +(OH)	179·21	181·69	179·56	176·73	178·51	180·28	180·13	182·26

TABLE III.   CATION PERCENTAGES WITH ASSOCIATED O AND (OH).

Lab. No.	V.14	V.22a	V.22b	V.119	V.123	V.177	V.178a	V.178b
a.p	0·16	0·13	0·13	0·05	0·13	0·08	0·08	0·05
il	0·08	0·12	0·12	0·08	0·14	0·08	0·08	0·06
cc	0·46	0·04	0·32	0·74	2·36	0·10	0·14	0·18
ms	–	0·24	0·04	–	6·58	0·24	0·20	0·08
or	0·70	0·70	0·70	0·75	0·20	0·60	0·90	1·30
ab	1·35	0·03	2·75	1·50	–	0·95	2·55	3·25
ne	–	0·80	–	–	–	–	–	–
an	0·15	–	–	0·80	–	–	–	–
c	3·45	1·34	0·26	2·06	–	2·05	2·40	–
ac	–	–	–	–	1·59	–	–	1·44
mt	0·42	0·12	0·15	3·78	2·13	1·41	0·36	0·06
hm	4·61	2·70	2·51	5·07	–	6·12	3·15	0·84
en	24·34	–	28·38	21·56	42·34	29·80	24·22	30·96
fo	64·26	93·77	64·65	63·63	44·52	58·56	65·91	61·80
TOTAL	99·98	99·99	100·01	100·02	99·99	99·99	99·99	100·02

TABLE IV.   MOLECULAR NORM OF THE SERPENTINE MINERALS.

the amount of aluminium was so small that not enough
remained for albite, after orthoclase had been calculated.
The sodium was allocated to acmite.   The high sodium
content of specimen V.178b also resulted in acmite.
Only two specimens have small amounts of anorthite.
The magnetite content of all the specimens, except V.119,
V.177 and V.123, is small and it is interesting to note
that the percentage ferro-iron is so low that the amount
of hematite in all the specimens is greater than the
amount of magnetite.   It is again only specimen V.123
which forms an exception in containing no hematite at
all.   All the specimens except V.22b, V.178b and V.123
contain fair amounts of corundum, a result of the rather
high alumina content of the non-fibrous specimens.   The
main normative constituents are enstatite and forsterite.
The former varies between 20% and 30% and the latter
between 58% and 66%.   Two exceptions exist: specimen
V.22a contains nearly 94% forsterite and no pyroxene and
is undersaturated to such an extent that even a little
nepheline is present;   specimen V.123 contains
approximately equal amounts of pyroxene and olivine.

b) Mineral composition based on a formula $Mg_6Si_4O_{10}(OH)_8$
   for serpentine

The mineral composition of the eight specimens
analysed chemically was determined using ionic percentages
(Table II) and the general formula $Mg_6Si_4O_{10}(OH)_8$ for the
serpentine minerals.   The elements were first allocated
to serpentine in the correct proportions and minerals
which are known to occur with serpentine were then built
out of the remaining material.   The elements Na, K, Ti,
P and Mn, which are present only as very small amounts,
and probably occur as isomorphous replacements in the
other minerals rather than forming minerals on their own,
were not allocated, but given as a "remainder", together
with any excess of other elements.

Following general procedure, the tetrahedral layer was filled first and then the octahedral layer. Using only Si in the tetrahedral layer it was found that in most cases there was an excess of Mg. If Al was added to the Si there was usually not quite enough Mg to fill the brucite-layer. From the relationship of Al to Fe^{+++} (Fig. 9) it was then decided to fill the octahedral layer with Fe^{+++}. The remaining Fe^{+++} was allotted to magnetite with Fe^{++} and if there still remained some Fe^{+++}, hematite was calculated. This procedure is not altogether satisfactory since some of the massive serpentinite also contains a brown spinel mineral which consists of Cr_2O_3, Al_2O_3 and Fe_2O_3 with some FeO and MgO. Most grains also had a rim (and sometimes a core as well) of magnetite. As already pointed out earlier, it was impossible to calculate the amount of this mineral present. If it be remembered, however, that Cr_2O_3 is not shown in the analyses and therefore probably included in the figure given for Fe_2O_3 and that there exists a serial relation- ship between the latter and Al_2O_3, then it can be seen that the inclusion of all Al^{+++} with Si would merely increase the percentage serpentine with the amount of spinel present. Since this amount is exceedingly small the results will not be materially affected. Calcite was formed from Ca and C, and whichever was present in excess was left with the "remainder". Excess Mg was calculated as brucite. It will be noticed that the allocations have been made rather arbitrarily but, since no hard and fast rules exist, the author has used his discretion in each case. The small percentages contained in the "remainder" are considered to lie within the range of experimental error of the chemical analyses and thus to be not of much importance.

The results are given below:

V.14: Dark green serpentinite

		%
Serpentine: $(Si_{12.49}Al_{1.41})$ $(Mg_{19.70}Fe'''_{1.15})$ $(O + OH)$		
13.90 ions + 20.85 ions + 62.55 ions	=	97.30
Magnetite: $Fe''_{0.04}Fe'''_{0.08}O_{0.16}$	=	0.28
Hematite: $Fe'''_{0.52}O_{0.78}$	=	1.30
Calcite: $Ca_{0.08}C_{0.08}O_{0.24}$	=	0.40
Remainder: $Ca_{0.05}$ $Na_{0.10}$ $K_{0.05}$ $Ti_{0.01}$ $P_{0.02}$ $Mn_{0.03}$ $(O+OH)_{0.48}$	=	0.74
TOTAL:		100.02

V.22a: Light green serpentinite

		%
Serpentine: $(Si_{11.35}Al_{0.62})$ $(Mg_{17.97})$ $(O+OH)$		
11.97 ions + 17.97 ions + 53.91 ions	=	83.85
Brucite: $Mg_{4.27}(OH)_{8.45}$	=	12.81
Magnetite: $Fe''_{0.02}Fe'''_{0.04}O_{0.08}$	=	0.14
Hematite: $Fe'''_{0.95}O_{1.44}$	=	2.39
Calcite: $Ca_{0.04}C_{0.04}O_{0.12}$	=	0.20
Remainder: $Na_{0.10}$ $K_{0.05}$ $Ti_{0.02}$ $P_{0.02}$ $Mn_{0.01}$ $C_{0.01}$ $(O+OH)_{0.41}$	=	0.62
TOTAL:		100.01

V.22b: Chrysotile asbestos

		%
Serpentine: $(Si_{13.52}Al_{0.34})$ $(Mg_{20.50}Fe'''_{0.29})$ $(O+OH)$		
13.86 ions + 20.79 ions + 62.37 ions	=	97.02
Magnetite: $Fe''_{0.02}Fe'''_{0.04}O_{0.08}$	=	0.14
Hematite: $Fe'''_{0.60}O_{0.90}$	=	1.50
Calcite: $Ca_{0.06}C_{0.06}O_{0.18}$	=	0.30
Remainder: $Na_{0.20}$ $K_{0.05}$ $Ti_{0.02}$ $P_{0.02}$ $Mn_{0.02}$ $Ca_{0.03}$ $(O+OH)_{0.70}$	=	1.04
TOTAL:		100.00

V.119: Dense apple-green serpentinite (picrolite)

%

Serpentine: $(Si_{12.16}Al_{1.02})$ $(Mg_{19.22}Fe'''_{0.55})$ $(O+OH)$

        13.18 ions + 19.77 ions + 59.31 ions = 92.26

Magnetite: $Fe''_{0.46} Fe'''_{0.92} O_{1.84}$ = 3.22

Hematite: $Fe'''_{1.27} O_{1.92}$ = 3.19

Calcite: $Ca_{0.13} C_{0.13} O_{0.39}$ = 0.65

Remainder: $Ca_{0.07}$ $Na_{0.11}$ $K_{0.05}$ $Ti_{0.01}$ $P_{0.01}$ $Mn_{0.01}$

                                  $(O+OH)_{0.40}$ = 0.66

TOTAL: 99.98

V.123: Brittle chrysotile asbestos

%

Serpentine: $(Si_{13.16}Al_{0.01})$ $(Mg_{19.33}Fe'''_{0.43})$ $(O+OH)$

        13.17 ions + 19.76 ion   + 59.27 ions = 92.20

Magnetite: $Fe''_{0.14} Fe'''_{0.27} O_{0.54}$ = 0.95

Calcite: $Ca_{0.45} C_{0.45} O_{1.35}$ = 2.25

Remainder: $Fe''_{0.24}$ $C_{1.16}$ $Na_{0.13}$ $K_{0.08}$ $Ti_{0.03}$ $P_{0.02}$

                           $Mn_{0.01}$ $(O+OH)_{2.94}$ = 4.51

TOTAL: 100.01

The remainder is rather on the high side, especially the percentage C and (O+OH). An alternate calculation, making dolomite instead of calcite and using all the iron in the octahedral layer is given below:

V.123: Alternate

%

Serpentine: $(Si_{13.16}Al_{0.01})$ $(Mg_{18.68}Fe'''_{0.70}Fe''_{0.38})(O+OH)$

      13.17 ions +   19.76 ions   + 59.27 = 92.20

                                           ions

Dolomite: $(Mg_{0.65} Ca_{0.45})$ $C_{1.10} O_{3.30}$ = 5.50

Remainder: $Na_{0.13}$ $K_{0.08}$ $Ti_{0.03}$ $P_{0.02}$ $Mn_{0.01}$ $C_{0.51}$

                                  $(O+OH)_{1.53}$ = 2.31

TOTAL: 100.01

This allocation of the elements gives a better fit than the first, but the percentage C and (O+OH) in the "remainder" is still high. To use up all the C to make carbonate will deprive the serpentine of 0.51 ions of Mg, and even if all the elements of the "remainder" are then substituted in the octahedral layer, they will not yet be able to fill it. In a thin section of this specimen a small amount of isotropic material, grains of carbonate and thin needles of magnetite were noticed. Since no magnetite is present in the second calculation, it is therefore also not satisfactory. No talc was noticed in thin section and the only alternatives are that either the brittle fibre has a different chemical formula than the one used in the calculation or that the isotropic material present is opal which would then explain the relatively high Si. Since opal is amorphous it was not possible to detect it by means of the X-ray analysis.

V.177: Dark green serpentinite

Serpentine: $(Si_{12.61}Al_{0.84})(Mg_{19.29}Fe'''_{0.90})(O+OH)$

			%
13.45 ions	+20.19 ions	+ 60.57 ions	= 94.21

Magnetite: $Fe''_{0.16} Fe'''_{0.32} O_{0.64}$ = 1.12

Hematite: $Fe'''_{1.30} O_{1.95}$ = 3.25

Calcite: $Ca_{0.04} C_{0.04} O_{0.12}$ = 0.20

Remainder: $Na_{0.07} K_{0.04} Ti_{0.01} P_{0.01} Mn_{0.02}$

$C_{0.02} (O+OH)_{1.04}$ = 1.21

TOTAL: 99.99

The presence of 3.25% hematite and 1.12% magnetite in this specimen is rather high and could probably include the brown spinel mineral noticed in thin section.

V.178a: Light green serpentinite

%

Serpentine: $(Si_{12.91}Al_{1.10})(Mg_{20.04}Fe'''_{0.98})(O+OH)$

          14.01 ions + 21.02 ions + 63.05   = 98.07
                                                           ions

Magnetite: $Fe''_{0.04} Fe'''_{0.08} O_{0.16}$ = 0.28

Hematite: $Fe'''_{0.15} O_{0.24}$ = 0.39

Calcite: $Ca_{0.04} C_{0.04} O_{0.12}$ = 0.20

Remainder: $Na_{0.18} K_{0.06} Ti_{0.01} P_{0.01} Mn_{0.02}$

                                    $C_{0.02} (O+OH)_{0.73}$ = 1.03

TOTAL: 99.97

V.178b: Chrysotile asbestos

%

Serpentine: $(Si_{13.92})(Mg_{20.09}Fe'''_{0.32}Al_{0.47})(O+OH)$

         13.92 ions + 20.88 ions + 62.64 ions   = 97.44

Hematite: $Fe'''_{0.01} O_{0.02}$.   = 0.03

Calcite: $Ca_{0.04} C_{0.04} O_{0.12}$ = 0.20

Remainder: $Na_{0.40} K_{0.09} Ti_{0.01} P_{0.01} Mn_{0.02}$

                                    $C_{0.01} (O+OH)_{1.81}$ = 2.35

TOTAL: 100.02

In this specimen the Mg is deficient to such an extent that, if Al is allocated as replacement of Si, not enough ions are left to fill the octahedral layer, even if all the elements are used. Substituting both Fe^{+++} and Al in the octahedral layer, with no replacements in the tetrahedral layer, gives a satisfactory result except that the (O+OH) in the "remainder" is slightly high. Whether an unbalanced replacement of 0.79 three-valent ions in the brucite layer with no replacements in the tetrahedral layer is possible, is not certain.

c) Standard Cell Calculations

In 1948 T.F.W. Barth suggested the calculation of the number of cations associated with 160 oxygen ions, including hydrogen, as a useful means of comparing rocks and minerals. He called this the Standard Cell of the rock (or mineral). Pentti Eskola (1954), however, showed that similar results could be obtained by comparing the number of oxygen and hydrogen ions associated with 100 cations. The Standard Cell has been calculated for eight serpentinite specimens and the results are given in Table III. The number of oxygen plus hydrogen ions varies from 176.73 to 182.26, and the group V.177, V.178a and V.178b forms an interesting series. As will be remembered, they represent the core, the rim and the fibre in the rim, of a boulder of serpentinite from Stolzburg Mine. From the field evidence there can be little doubt that the rim and the core were derived from one and the same rock. Comparing the amounts of (O+OH) it will be seen that it is approximately the same for the two specimens. The chrysotile (V.178b), however, has a slightly greater amount and it would appear then that during the formation of the chrysotile from the serpentinite (V.178a) a small quantity of water must have been added. This is in agreement with the findings of Hall (1929, p.247). In comparing also the other elements it can be seen that the dark green serpentinite can be changed into light green serpentinite by subtracting:

$$3.67 \; Fe^{III}$$
$$0.35 \; Fe^{II}$$
$$0.85 \; O$$
$$\overline{}$$
$$4.87 \; \text{ions, representing } 10.01$$

positive valences; and by adding:

$$0.80 \; Si$$
$$0.73 \; Al$$
$$2.09 \; Mg$$
$$0.02 \; Ca$$
$$0.32 \; Na$$
$$0.06 \; K$$
$$0.70 \; (OH)$$
$$\overline{}$$
$$4.72 \; \text{ions, representing } 10.69$$

positive valences.

The chrysotile can in the same way be derived from
the light green serpentinite by adding:

$$\begin{array}{ll}
3.13 & Si \\
0.57 & Mg \\
0.62 & Na \\
0.08 & K \\
0.64 & O \\
1.49 & (OH)
\end{array}$$

6.54 ions, representing 14.61

positive valences; and by subtracting:

$$\begin{array}{ll}
2.18 & Al \\
2.01 & Fe^{\text{III}} \\
0.11 & Fe^{\text{II}} \\
0.01 & Ti \\
0.01 & P \\
0.04 & C
\end{array}$$

4.36 ions, representing 13.04

positive valences.

In Barth's work all calculations were referred to a
volume of 160 oxygen ions and the valences therefore
balanced.   Since the oxygen content here is variable the
valences need not necessarily balance.

X-ray Examinations

Twelve specimens were selected for X-ray analyses.
All the recordings were done by Dr W.R. Liebenberg of the
Government Metallurgical Laboratories on an XRD3 General
Electric apparatus.   Filtered cobalt radiation was used
with a 3° beam slit and a 0.2° slit on the detector.

Most specimens were packed in the ordinary holder,
but the fibrous specimens were packed in a special holder
to prevent orientation as far as possible.   No difficulty
was encountered in grinding most of the massive serpentinite
specimens to -300 mesh.   With the chrysotile, however, it
was not so easy.   A pair of steel scissors was first used
to cut the fibre as fine as possible.   (In some cases,
where the fibre was rather talcy - specimen V.211 - a
razor blade was used instead).   Small amounts at a time
were then ground down further in an agate pestle and mortar.

To prevent "clogging" an attempt was made to grind the fibre
mixed with alcohol. It was found, however, that this did
not make any appreciable difference. Certain lines
observed in the dry-ground sample were absent in the
specimen ground in alcohol and vice versa. To serve as
an example only the results of specimen V.22b are given
for the material ground dry as well as ground in alcohol,
(Table V). All other results are for specimens ground in
the dry state.

It will be noticed that in accordance with the work of
previous workers, the lines of the massive serpentinites
(predominantly antigorite) are much sharper than the lines
of the chrysotile specimens (Figs.10A and B). The results
are given in Table V.

The most persistent lines were the following:
7.19 - 7.34, 4.37 - 4.75, 3.61 - 3.66, 1.533 - 1.537 and
1.307 - 1.310. They were observed in all the specimens
and are therefore common to both antigorite and chrysotile.
Each of these lines varied within narrow limits, as given
above. The explanation of these variations is not clear.
Experimental error, which is considered to be about 0.05 in
the small angle (7θ) region and about 0.003 in the large
angle (35θ) region, can account for some variation but not
for all. The variations also do not seem to have any
relationship to the percentage chrysotile or antigorite.
In plotting the d-values against the chemical composition
it was found that only the 7.19 - 7.34 lines showed a
relationship with the percentages Fe^{+++}/Mg (Fig.11A) on
the one hand and with the percentages Al/Si (Fig.11B)
on the other. Whether the other variations have any
structural importance is not certain.

Of the remaining lines some were fairly persistent,
some less so, and some lines were observed only in one
or two specimens. Of the fairly persistent lines the
2.43 - 2.45 and 2.093 lines are the most important.
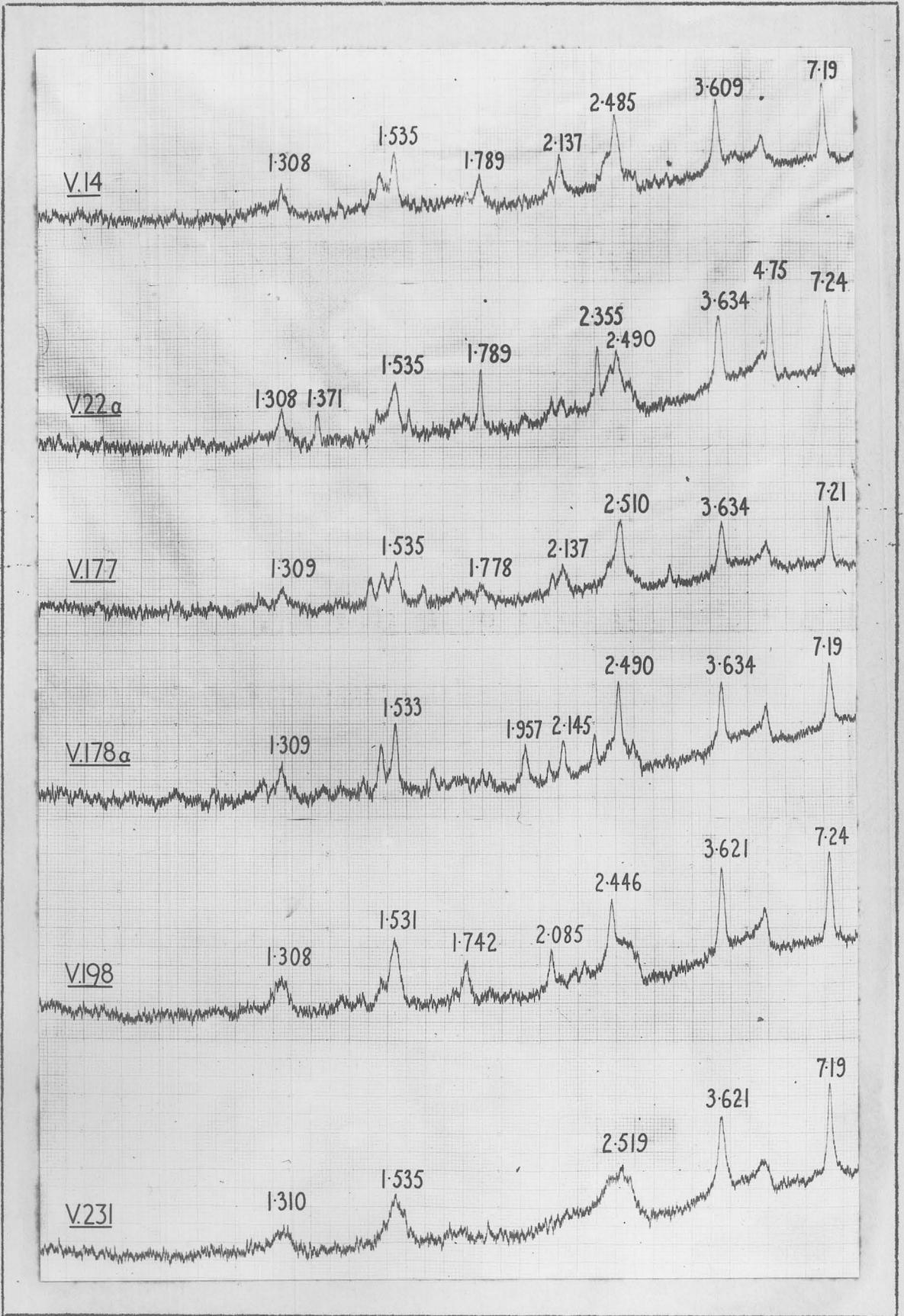
Fig.10 A

X-ray diffraction charts of massive serpentinite. The d-spacings of the strongest reflections are given in Angstrom units.(CoK$_\alpha$ radiation, logarithmic recording).
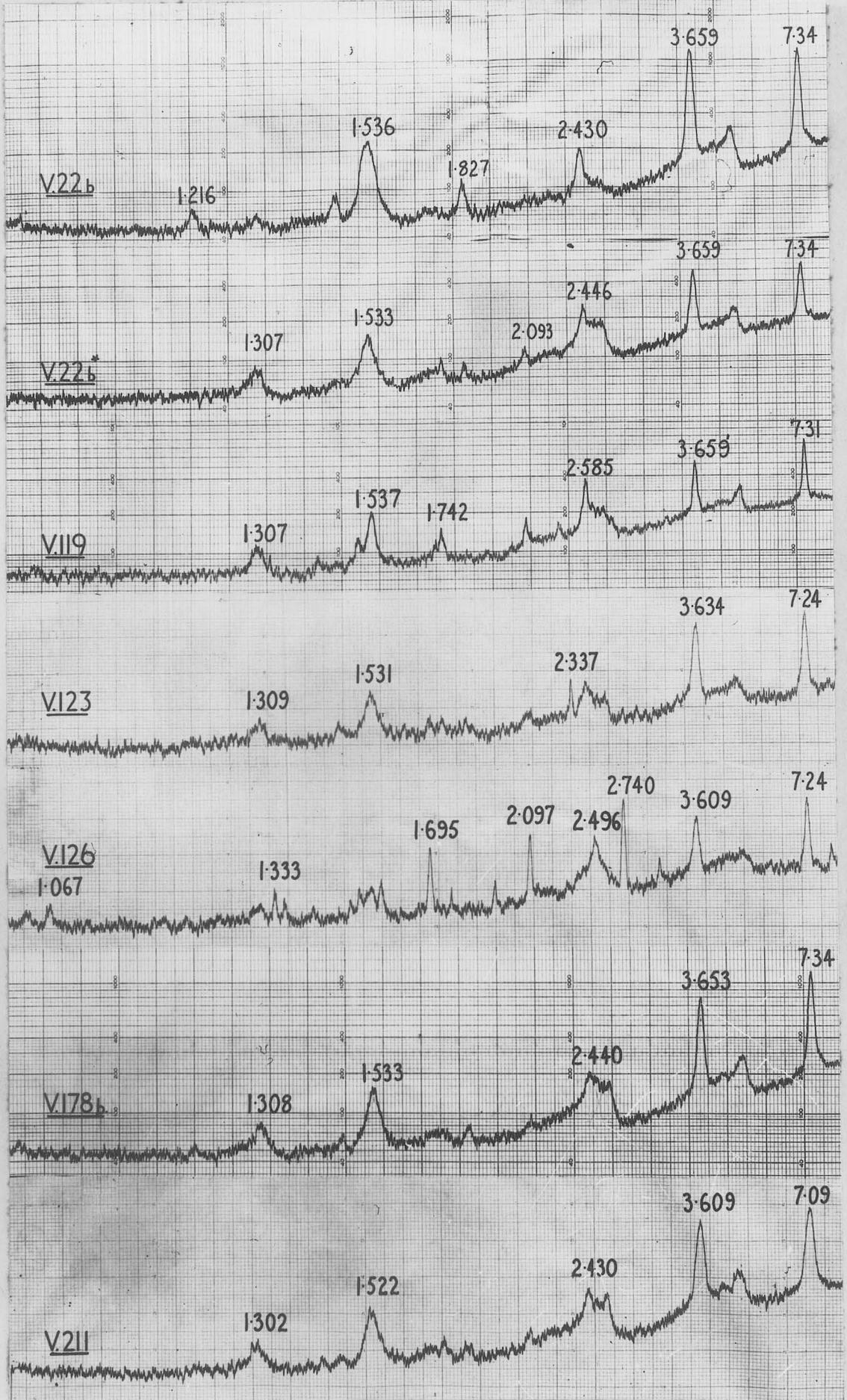
Fig.10 B

X-ray diffraction charts of chrysotile and picrolite. The d-spacings of the strongest reflections are given in Angstrom units.(CoK$_\alpha$ radiation, logarithmic recording).
* Specimen ground in alcohol.
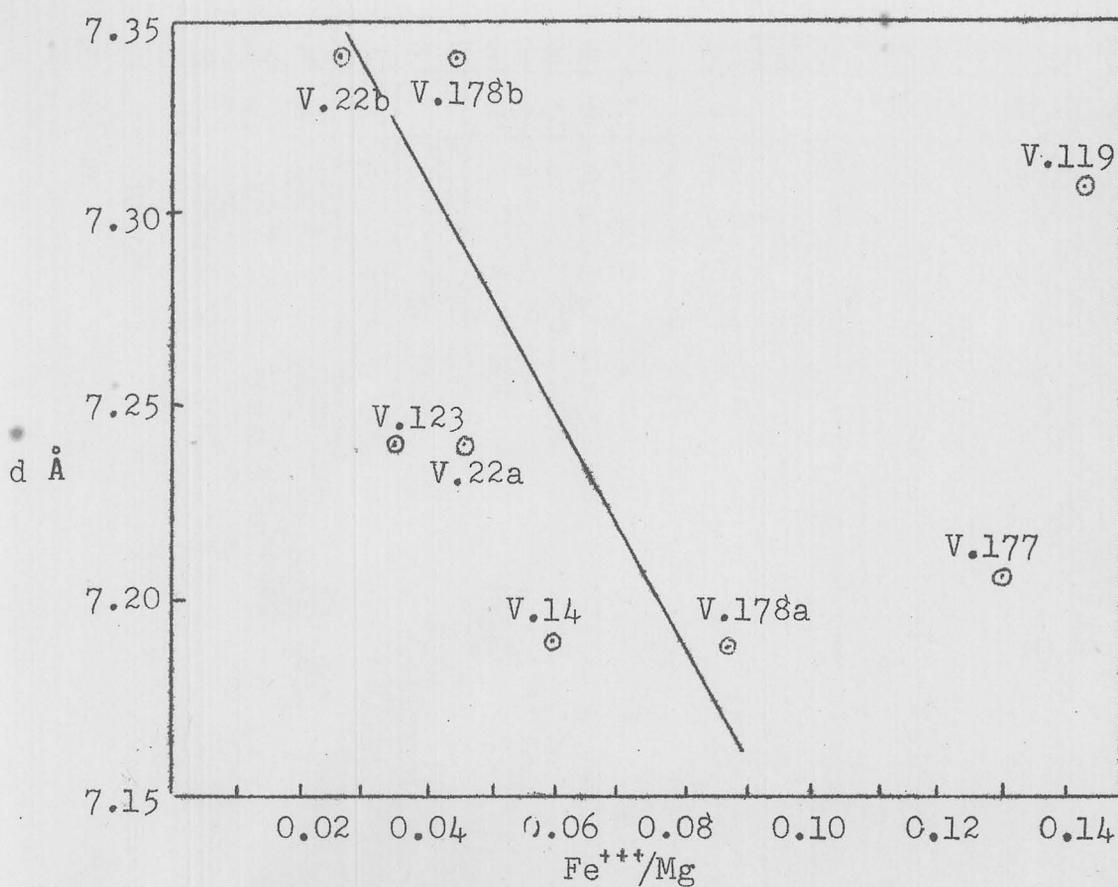
Graph showing the variation of d-values against
the iron magnesium ratio in the serpentine minerals.

Fig.11 A
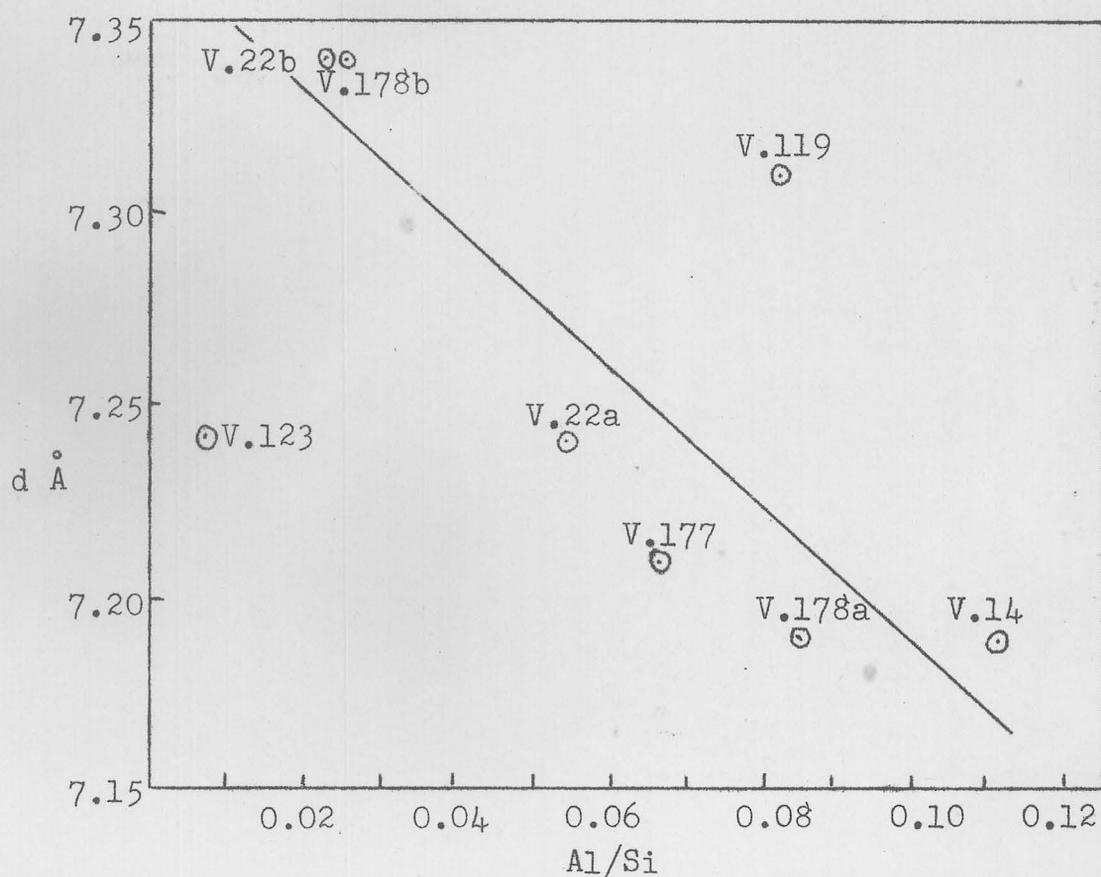
Graph showing the variation of d-values against
the aluminium silicon ratio. The low Al/Si ratio
of specimen V.123 could be explained by the
presence of opal impurity.

Fig.11 B

V.14		V.22a		V.22b.		V.22b*		V.119		V.123	
Int.	dA.	Int.	dA.	Int.	dA.	Int.	dA.	Int.	dA.	Int.	dA.
	–	–	–		–		–		–		–
100	7.19	80	7·24	98	7·34	100	7·34	100	7·31	100	7·2
20	4.55	100	4.75	15	4·49	26	4.49	24	4·59	14	4·3
	–		–		–	–			–		–
68	3·609	56	3·634	100	3·659	95	3·659	66	3·659	79	3·6
	–		–		–		–		–		–
	–		–		–		–		–		–
	–		–		–		–		–		–
	–	12	2·600		–	26	2·597		–	9	2·5
	–		–		–		–		–		–
56	2·485	30	2·490				–		–		–
	–	19	2·451	11	2·430	44	2·446	48	2·454	14	2·4
	–		–		–		–		–		–
5	2·367	33	2·355						–	18	2·3
	–		–					9	2·271		–
19	2·137	7	2.141		–		––		–		–
7	2.087	7	2.087		–	10	2·093	12	2·093	7	2.10
	–		–		–		–		–		–
	–		–	6	1.827	7	1·825		–	5	1·82
10	1.789	18	1.789		–		–		–		–
	–		–		–		–		–		–
	–		–		–	9	1.743	12	1.742	5	1·7
	–		–		–		–		–	6	1·6
	–	7	1.579		–		–		–		
	–		–		–		–		–		–
22	1.535	16	1.535	18	1.536	28	1.533	25	1.537	16	1.5
	–		–		–		–	16	1·507		
8	1.502	7	1.491		–		–		–		–
12	1.481				–						
	–		–	4	1·461				–	5	1.4
6	1.412		–		–		–		–		–
	–	7	1.371		–		–		–		
	–		–		–		–	6	1·329		
	–		–		–		–		–		
11	1·308	8	1·308	2	1·309	11	1·307	11	1·307	7	1.
	–		–		–		–		–		
	–		–	3	1.216		–		–		
	–		–		–		–		–		
	–		–	–	–		–		–	4	1.
	–		–	2	1.045		–		–		
									–	6	0.

TABLE   V.

X-RAY DIFFRACTION SPACINGS FOR THE SERPENTINE MINERALS.

V.22b*		V.119		V.123		V.126		V.177		V.178a.		V.178b.		V.198		V.211		V.231	
Int.	dA.	Int.	dA.	Int.	dA.	Int.	dA.	Int.	dA.	Int.	dA.	Int.	dA.	Int.	dA.	Int.	dA.	Int.	dA.
–		–		–		21	9.25	–		–		–		–		–		–	
0	7.34	100	7.31	100	7.24	94	7.24	100	7.21	100	7.19	100	7.34	100	7.24	100	7.09	100	7.19
6	4.49	24	4.59	14	4.37		–	30	4.58	36	4.39	11	4.49	24	4.53	18	4.41	18	4.45
–		–		–			–		–		–		–		–	20	4.03	–	
5	3.659	66	3.659	79	3.634	61	3.609	64	3.634	73	3.634	68	3.653	80	3.621	86	3.609	64	3.621
–		–			–	15	3.104		–		–		–		–		–		–
–		–			–		–	8	2.942		–		–		–		–		–
–		–			–	100	2.740		–		–		–		–		–		–
6	2.597		–	9	2.584		–		–	16	2.603	9	2.590		–		–		–
–		–			–		–		–		–		–		–	15	2.554		–
–		–			–	40	2.496	84	2.510	89	2.490		–		–		–	20	2.519
4	2.446	48	2.454	14	2.432		–		–		–	13	2.440	44	2.446	17	2.430		–
–		–		18	2.337		–		–	19	2.328		–		–		–		–
–		9	2.271		–		–		–		–		–		–		–		–
–		–			–		–	19	2.137	18	2.145		–		–		–		–
0	2.093	12	2.093	7	2.105	46	2.097	13	2.085	10	2.066	3	2.093	12	2.085	5	2.085		–
–		–			–	12	1.937			18	1.957		–		–		–		–
7	1.825		–	5	1.825		–		–	6	1.816	3	1.828		–		–	4	1.810
–		–			–		–	10	1.778	7	1.789		–		–	4	1.803		–
–		–			–	10	1.768		–		–		–		–		–		–
9	1.743	12	1.742	5	1.734		–		–		–		–	10	1.742	5	1.730		–
–		–		6	1.697	35	1.695	8	1.697		–		–		–		–		–
–		–			–		–	11	1.604	9	1.634		–		–		–		–
–		–			–	14	1.556				–		–		–		–		–
28	1.533	25	1.537	16	1.531	8	1.535	30	1.535	36	1.533	11	1.533	19	1.531	13	1.531	11	1.535
		16	1.507		–		–				–		–		–	15	1.522		
	–		–		–	8	1.504	20	1.502	20	1.499		–		–		–		–
	–		–		–	6	1.483	15	1.476				–		–		–		–
	–		–	5	1.458		–		–	6	1.458	2	1.464		–		–		–
	–		–		–		–		–	5	1.411				–		–		–
	–		–		–	7	1.350		–						–		–		–
	–	6	1.329		–	12	1.333		–		–				–		–		–
	–		–		–		–		–		–				–		–	4	1.317
11	1.307	11	1.307	7	1.309		–	14	1.309	14	1.309	4	1.308	6	1.308	6	1.302	4	1.310
	–		–		–		–	11	1.271	8	1.278		–		–	5	1.291		
	–		–		–		–		–		–		–		–		–		–
	–		–		–		–	9	1.158		–				–		–		–
	–		–	4	1.108		–		–				–		–		–		–
	–		–		–	7	1.067		–				–		–		–		–
	–		–	6	0.991				–				–		–		–		–

* Ground in alcohol.

The line which varies between 2.48 and 2.52 was observed
only in the massive serpentinite specimens and not in
chrysotile, except in specimen V.126 which is composed of
"pseudo"-fibre.   In most specimens the lines were less
than 2.50d$\overset{o}{A}$.   It will also be noticed that in nearly all
the massive serpentinite specimens a pair of lines 1.53
and 1.50 was recorded and not the characteristic pair of
antigorite at 1.563 and 1.541.   From the work of Whittaker
and Zussman (1956) this would indicate that antigorite is
rather scarce or even absent in most of the serpentinites
and that the main mineral is lizardite.   Whittaker and
Zussman (1956, p.121), however, record a pair of lines
1.534 and 1.509 in the column giving the averages of five
antigorite specimens.   On the same page the spacings of
specimens (29) and (30) are given without that pair but
containing a pair 1.56 - 1.54.   In the description,
however, (p.120) it is stated that these two specimens were
splintery, their patterns had fewer lines than the other
antigorite, and that their peaks were broader.   To the
present author this would indicate that these specimens
were not very suitable for arriving at definite conclusions
and he therefore feels that the presence of the pair
1.53 - 1.50, rather than the pair 1.56 - 1.54, does not
necessarily indicate lizardite rather than antigorite.
The author further feels that since orientation of the
serpentine minerals often results in the disappearance of
certain lines and chemical variation may cause small shifts
in the lines, caution should be exercised in giving new
names until a very much greater number of specimens has
been investigated.   It may also be mentioned that very
often specimens are so fine-grained that it is impossible
to obtain samples that are indubitably pure.   Small
amounts of carbonate, talc or magnetite may then add extra
lines to the pattern and complicate interpretation.

Differential Thermal Analyses

Five specimens of massive serpentinite and four specimens of chrysotile were selected for Differential Thermal Analyses. The apparatus used is similar to the one described by Schmidt and Heystek (1954). Two furnaces with horizontal alundum tubes, 12 inches long and 2 inches in diameter and wound with Kathal wire, were used. The furnace temperature was controlled by means of a manually operated variac and the temperature recorded on a pyrometer. The temperature was increased at a constant rate of $15^{\circ}C$ per minute. The specimen holder consisted of a nickel block with two holes $\frac{1}{2}$ inch in diameter. A platinum/platinum 13% rhodium thermo-couple was used and the differential temperatures recorded on a Cambridge spot-light type galvanometer. The sensitivity was controlled by a variable external resistance from 10,000 to 1 ohm with an accuracy of 0.1%. Furnace temperatures were checked by means of the quartz inversion temperatures. Keith and Tuttle (1952) have shown that the inversion temperature of 95% of all natural quartz will fall in a range of $2.5^{\circ}C$.

Calcined alumina, ground down to -100 mesh, was used as inert material and where possible the specimens were also ground down to -100 mesh. It was found, however, that it was not always possible to grind the chrysotile down to that size. The specimens were packed down under even pressure in the specimen holder. The chrysotile, however, remained "springy" and could not be packed down to the same density as the other specimens.

The reproducibility of D.T.A.-curves, which has been studied by Webb, is affected by the following factors (Schmidt and Heystek, 1954):

a) Rate of temperature rise;

b) Diameter of sample holder hole;

c) Thickness of differential thermocouple wire;

d) Position of thermocouple beads in sample;

e) Density of packing of sample;

f) The particle size of the sample.

The first four factors can be kept constant fairly easily but with the serpentine minerals the last two can seldom be duplicated. The more fibrous the specimen, the more difficult it will be to grind it down to a specific size and to pack it into the holder to a desired density.

The author is of opinion that many of the differences recorded in the D.T.A.-graphs of the serpentine minerals could be due to this difficulty.

The results of the analyses are given in Figures 12A and 12B. Runs were made from room temperature to 1000°C. It will be noticed that all the specimens gave similar results: an endothermic peak around 750°C which is followed by an exothermic peak around 840°C.

The endothermic peak was found in different samples to vary from 720°C for specimen V.123 to 778°C for specimen V.119, that is a range of 58°C. No explanation for this variation could be found. It may be mentioned, however, that the size (surface area) of the peaks of the massive serpentinites (antigorite) was on the whole some-what greater than that of the fibrous specimens. This is probably due to the difference in packing density. The indication of a double peak in specimen V.123 is probably due to the presence of dolomite.

It was found that the exothermic peak varied over a smaller range, namely 34°C i.e. 821°C for specimen V.123 and 855°C for specimens V.22b and V.211. Again the variation cannot be explained. It will also be noticed that similar to the case of the endothermic peaks the exothermic peaks for the chrysotiles were very much
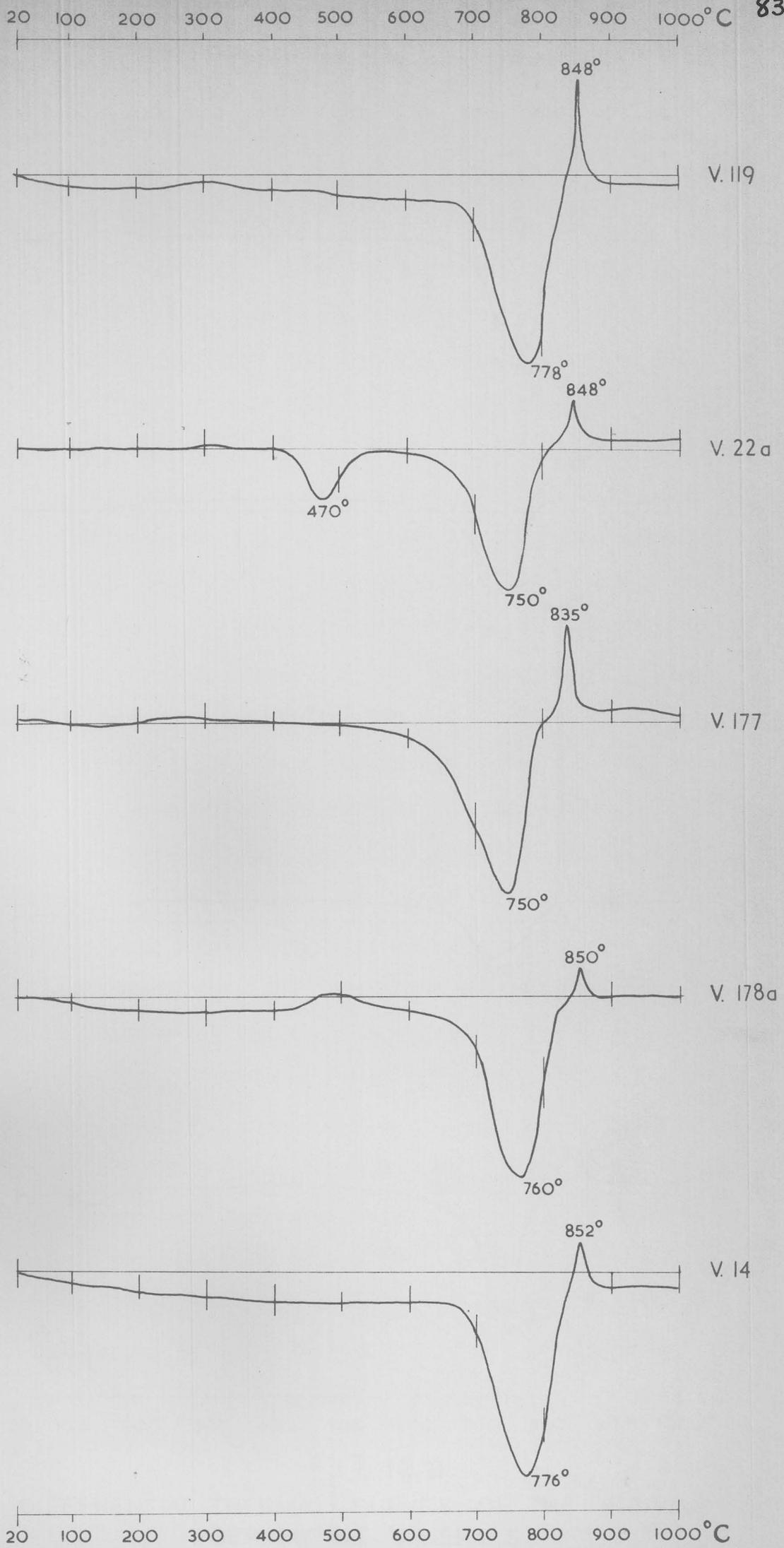
FIG. 12 A.

DIFFERENTIAL THERMAL CURVES OF THE MASSIVE
SERPENTINE MINERALS

(Heated at 15°C per minute, Pt/Pt-Rh thermocouple, 400∿ in external circuit)
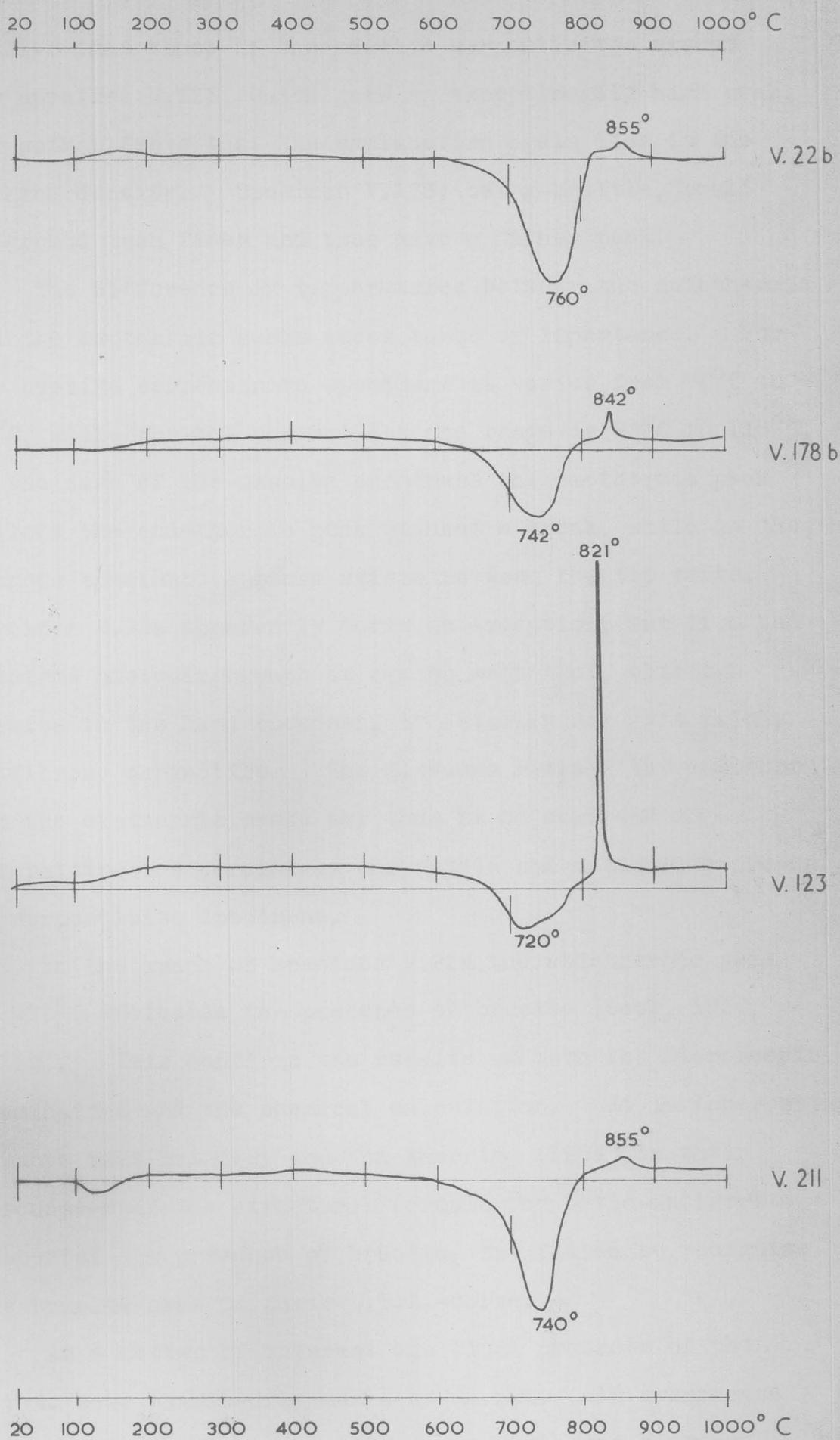
20 100 200 300 400 500 600 700 800 900 1000° C

855°

V. 22 b

760°

842°

V. 178 b

742° 821°

V. 123

720°

855°

V. 211

740°

20 100 200 300 400 500 600 700 800 900 1000° C

FIG. 12 B.

DIFFERENTIAL THERMAL CURVES OF THE FIBROUS
SERPENTINE MINERALS

(Heated at 15°C per minute, Pt/Pt-Ph thermocouple, 400 ᴧ in external circuit)

smaller than those of the massive serpentinites except
for specimen V.123, which gave an exceptionally high peak.
The author feels that the explanation again lies in the
packing density. Specimen V.123, being brittle, could
be ground much finer and thus gave a higher peak.

The difference in temperatures between the endothermic
and the exothermic peaks seems to be of importance. For
the massive serpentinite specimens it varies from $70^{\circ}C$ to
$90^{\circ}C$, while for the chrysotiles the range is $95^{\circ}C$ to $115^{\circ}C$.
In the case of the massive specimens the exothermic peak
follows the endothermic peak without a break, while in the
fibrous specimens a pause exists between the two peaks.
Specimen V.22a apparently forms an exception, but from the
electron photomicrograph it can be seen that, although
massive in the hand specimen, it actually consists mainly
of fibrous chrysotile. The distance between the endothermic
and the exothermic peaks may thus be of some use in
determining the percentage chrysotile and antigorite present
in serpentinite specimens.

In the graph of specimen V.22a the endothermic peak
at $470^{\circ}C$ indicates the presence of brucite (Beck, 1950,
p.515). This confirms the results of both the microscopic
examination and the chemical calculation. It is interesting
to note that Brindley and Von Knorring (1954) in their
discussion of the structural formula for ortho-antigorite
suspected the presence of brucite, but failed to recognize
the brucite peak in their D.T.A.-curve.

As a matter of interest the final products of the
D.T.A. were examined by means of X-rays. In every case
olivine was found but no difference was noted between
the end products of chrysotile and antigorite.

Small variations were observed in the spacings for
the olivine. From the chemical analyses of the original
specimens it can be seen that the percentage iron varies
considerably. It is expected therefore that the percentage

forsterite and fayalite in the olivine, formed from the
serpentinite, should also vary.   This would adequately
explain the small variations.

Electron Microscope Studies

As a result of the microscopic, X-ray and D.T.A.-
studies the author formed the opinion that certain
serpentinite specimens contain both the serpentine minerals,
antigorite and chrysotile, even though no fibrous structure
could be seen in the hand specimen.   Since the former has
a layered structure and the latter a tubular structure, it
is to be expected that antigorite would have a flaky habit
while chrysotile would be fibrous.   Due to the very small
size of the minerals the microscope was not of much avail
and it was decided to try the use of the electron microscope.
While this work was in progress, the paper of Nagy and Faust
(1956) on "serpentinites: a natural mixture of chrysotile
and antigorite" was published.   The outcome of the present
investigation firmly supports the work of Nagy and Faust.

At the National Physical Research Laboratories of the
C.S.I.R., Pretoria, electron photomicrographs of 9
specimens, six of massive serpentinite and three of
chrysotile, were taken by Dr J.J. Fourie.

The specimens were prepared as follows: Firstly a
specimen was ground down as fine as possible.   This
powder was then mixed with water and allowed to stand for
some time to allow the coarser particles to settle.   An
attempt was also made to suspend the powder in alcohol
and in ammoniac, but it was found that both these media
were unsuitable because coagulation of the small
particles took place.   A drop of water, containing only
the finest fraction of the specimen was then allowed to
dry on a thin film of silicon-monoxide in a special
small holder.   All specimens were photographed directly

and tungsten casts were made only of specimens V.211 and V.177. The photomicrographs were taken at a magnification of 17,500 (Plates 48 to 61).

The results are most interesting. Of the six massive serpentinites only specimens V.177, V.178a and V.231 were composed of flaky minerals alone (Plates 58, 59 and 60). Of the other three specimens, specimen V.14 (Plate 50) contained both fibrous and flaky minerals, while specimens V.22a and V.119 (Plates 52 and 53), although massive in hand specimen, were composed nearly exclusively of fibrous particles. The latter three specimens are all from the Havelock Mine. It would thus appear that at Havelock the hangingwall blue serpentinite (V.14), which is composed of antigorite and chrysotile, grades downwards into a serpentinite (V.22a) composed nearly entirely of sub-microscopic chrysotile needles. This chrysotile then subsequently recrystallized along fractures to form the longer chrysotile fibres (V.22b) which are of economic interest. In a few rare cases cracks have been filled with dense apple-green serpentine (picrolite), (V.119), which is also fibrous under the electron microscope, but for some reason or other did not form long oriented fibres. From the electron photomicrograph it can also be seen that these fibres are much shorter and thicker than those of the chrysotile veins. The tubular nature is, however, clearly demonstrated (Plate 52).

Of the three chrysotile specimens it can be seen that the one from the New Amianthus Mine (V.211), (Plates 55 and 56), consists of much thinner fibres than the specimen from Havelock (V.22b), (Plate 51). The specimen of brittle fibre (V.123), (Plate 54), also from the Havelock Mine, consists of fairly fine fibres, which, however, tend to remain in bundles and do not easily split into separate fibres. This phenomenon could be due to

the presence of opal which, from the microscope and chemical studies, is suspected to be present.   Such a coating of opal would also explain the brittleness of the fibre.

Three inch long talcified fibre from the Congo-Vaal Asbestos Mine (V.254), (Plate 57), was also photographed under the Electron Microscope.   It can be seen that the fibrous nature is nearly completely destroyed and that the specimen now consists mainly of flakes of talc.

V   THE NATURE AND ORIGIN OF SERPENTINITE AND CHRYSOTILE ASBESTOS

Veins of chrysotile asbestos are always associated with serpentinite.   In a discussion of the origin of chrysotile it is therefore necessary also to consider the nature and origin of the serpentinite, even though the two may not necessarily have been formed by the same processes.

A. SERPENTINITE

Two types of serpentinite are found in nature:

1) the relatively small occurrences of serpentinized dolomite and
2) the large bodies of massive serpentinite usually restricted to folded mountain regions.

1.   Serpentinized dolomite

a) Mode of occurrence:

Serpentinization of dolomite is normally associated with intrusive basic sills, but a few occurrences along the contacts of diabase dykes are also known.   In the case of sills the serpentinite is found as streaks or bands parallel to the bedding of the dolomite, not more than a few inches wide and seldom continuous along strike for more than a few tens of feet.   These bands may be

directly in contact with the sill or may be separated from it by as much as four to five feet of de-dolomitized limestone. A particular zone of serpentinite may end abruptly with another starting on a different horizon, either nearer or further away from the diabase sill. Two or more parallel bands may also occur.

The contact of the serpentinite with the country rock may be sharp, but more often it grades into a rock composed of calcite and finely disseminated serpentine. The latter usually has a light green colour but may also be yellowish or brownish. Chocolate brown streaks sometimes found associated with the serpentinite contain a high percentage of iron and aluminium. Impurities in the dolomite are often "pushed out" to form dark borders along zones of serpentinization (Plate 47).

In the case of dykes serpentinization is known to have occurred in two different ways. For example, on the farm Elandshoek 139, irregular patches of serpentinized dolomite transgressing the bedding occur next to a near-vertical dyke. In places contorted bands of serpentine follow the bedding of the dolomite (T.W. Gevers, unpublished report). On the other hand, on the farm Paardekraal M6, Postmasburg district (outside the area under discussion) it was found that the serpentinization occurred entirely as bands and streaks at several separate horizons parallel to the bedding of the dolomite. The serpentinite was restricted to zones about ten feet wide on both sides of the dyke.
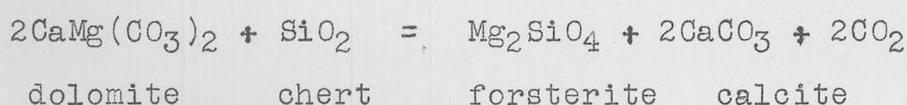
b) Origin:

The serpentinization of the dolomite is almost certainly genetically connected with the intrusive diabase sills or dykes. The Transvaal dolomite is normally composed of dolomitic limestone rather than pure dolomite; in other words the percentage magnesium

is rather low.   It is also known that the latter varies
from place to place.   In the dolomite bands and lenses,
as well as zones of finely disseminated chert, are often
found parallel to the bedding at various horizons.   Both
magnesia and silica are therefore available in the dolomite
and for the conversion to serpentine only water will have
to be derived from an outside source.   The intrusion of
a basic dyke or sill could supply the necessary water and
also increase the temperature of the wall rock so that
reaction between the silica, magnesia and water can take
place.   In the case where irregular patches of
serpentinized dolomite occur along the contacts of dykes
a certain amount of additional silica was probably derived
from the intrusive.   The thermal conducitivity of dolomite
is low and heat transfer would probably take place mainly
through the medium of the solutions derived from the
igneous rock.   Poldervaart (1950, p.242) suggests that
this solution would mingle with water already present in
the dolomite and would thus lose its identity.   The only
functions would be transfer of heat and solution of the
dolomite.   Poldervaart further feels that thermo-
diffusion will concentrate magnesium near the intrusion
and calcium further away.   This process will result in
the formation of serpentine next to the dyke, then talc,
and calcite beyond.   To the present author this theory
does not seem to fit the observed facts adequately.
De-dolomitized (calcitic) rock is often found near the
basic intrusion and the bands of serpentinite further
away.   Talc is found only in the vicinity of faults or
in dolomite containing a large amount of chert, and was
nowhere observed to occur in the sequence serpentine -
talc - calcite as suggested by Poldervaart.   It is felt
that the distribution of the zones of serpentinized
dolomite is dependant on the distribution of silica in
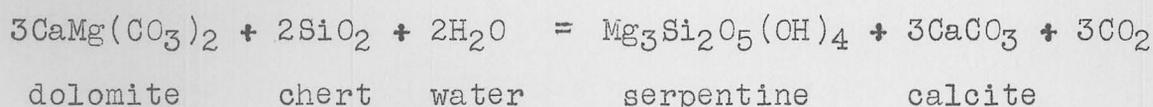the original rock and that with an increase of temperature

and the presence of sufficient water, reaction between the
magnesia, silica and water would take place to form
serpentine. From the work of Bowen and Tuttle (1949)
and of Yoder (1951) it has been shown that serpentine
(chrysotile) is unstable above a temperature of 500°C.
If the temperature of the dolomite close to the intrusive
were raised to 900 - 1000°C as Poldervaart (1950, p.240)
has suggested, it would be expected that olivine would form
initially and that serpentinization would begin only after
the temperature had fallen below 500°C. Further away from
the sill where temperatures remain lower serpentine would
form directly without olivine as an intermediate stage.
Once reaction has begun a chemical potential will be set up
(Barth, 1952, p.314) and magnesium will migrate towards
the zone of serpentine formation leaving behind a rock
rich in calcite.

The following equations represent the probable
reactions:

above 500°C:

$$2CaMg(CO_3)_2 + SiO_2 = Mg_2SiO_4 + 2CaCO_3 + 2CO_2$$
dolomite   chert   forsterite   calcite

below 500°C:

$$3CaMg(CO_3)_2 + 2SiO_2 + 2H_2O = Mg_3Si_2O_5(OH)_4 + 3CaCO_3 + 3CO_2$$
dolomite   chert   water   serpentine   calcite

Olivine, altering to serpentine, has been noted in
dolomitic limestone within the metamorphic aureole of
the Bushveld Complex. However, in the normal cases
associated with dykes or sills, no indication of the
existence of original olivine has been found in any of
the specimens examined. It must, therefore, be inferred
that the temperatures did not rise high enough for
olivine to have been formed and that serpentine was the
initial product.

The amount of serpentinization found along a basic sill usually seems to be directly related to the thickness of the intrusion. It has been found, however, that relatively thin sills sometimes caused extensive serpentinization along their contacts, while in other cases very thick sills have only a negligible quantity of serpentine associated with them. The temperature of the intrusion as well as the amount of volatiles is probably the controlling factor. It should be mentioned, however, that the composition of the rock in contact with the intrusive will also affect the degree of serpentinization. It has been found in the case of sills which cut across the bedding of the dolomite that a wide zone of serpentinization is produced in one place whereas else-where serpentinization is very limited. The latter is the case where the dolomite is highly siliceous or cherty and talc or tremolite are then formed instead of serpentine. Although this could not be definitely established, because of poor exposures, diabase sills in the dolomite seem to occur preferentially along the contact between a chert zone and massive dolomite. Serpentinization would then be expected only on one side of the sill.

As far as could be established the composition of the basic intrusives had no influence on the amount of serpentinization. In most cases the sills and dykes were composed of diabase but on Elandshoek the dyke graded into pyroxenite. The difference in composition did not seem to influence the amount of serpentinization occurring along the dyke (T.W. Gevers, unpublished report).

2. Massive serpentinite

a) Nature:

The massive serpentinites, like those of the Jamestown Complex, often contain remnant grains of olivine or

pyroxene and are considered by most geologists to be the serpentinized equivalents of dunite, peridotite or pyroxenite. This process of serpentinization is also believed by many to be intimately connected with the origin of the ultrabasic itself.

The ultrabasic rocks and their serpentinized equivalents usually occur as steeply inclined sills or lenses in orogenic areas, ("Alpine" type of Benson, 1926, p.6). They are normally concordant with the enclosing sediments, but local transgressions are common. The country rocks are often highly folded and faulted, which complicates the interpretation of the true relationships. The individual bodies may be large and extend for long distances along strike. Usually they are small, however, and are often arranged en echelon, (Turner and Verhoogen, 1951, p.240).

There exists an almost constant association of alpine type peridotites and serpentinites with geosynclinal sediments like graywackes and cherts. Basalts, spilites and keratophyres are also common associates of the ultra-basics (Turner and Verhoogen, 1951, p.240). Gabbroic rocks of plutonic character are, however, scarce and only found as small isolated bodies. Sills and dykes of diabase, younger than the ultrabasic rocks, are often encountered. Turner and Verhoogen (1951, p.242) also mention the association of calc-silicate rocks, containing grossularite, hydrogrossular, vesuvianite, zoisite and clino-zoisite, with peridotite. They consider these calcium bearing rocks to be of metamorphic (hydrothermal) origin.

The basalts, gabbroic rocks and ultrabasics, although of different nature, are usually considered to be co-magmatic. They are often altered to chlorite-epidote rocks and serpentinites and are collectively known as ophiolites (Barth, 1951, p.184). Other dunites and

peridotites, like those of the Bushveld Complex and the Great Dyke of Rhodesia, fall in another category. They form part of the layered complexes and are usually associated with pyroxenite.

The dunite and the pyroxenite are usually composed of magnesium rich olivine and ortho-pyroxene respectively. Cooke (1937, p.61) mentions the presence of diallage in the pyroxenites of the Thetford area, and at the Havelock Mine remnants of monoclinic pyroxene were found in serpentinite at two localities. The pyroxenite dyke at the Stolzburg Mine also contains remnants of clino-pyroxene. The serpentine derived from these rocks contains both the serpentine minerals antigorite and chrysotile in varying amounts. Accessory minerals in the form of chlorite, brucite, magnetite, chrome-spinel, talc, magnesite, dolomite, stichtite and barbertonite may also be present.

All gradations from unaltered ultrabasic through partly altered rock to pure serpentinite have been reported. At Shabani, Keep (1929) found a definite relationship between the degree of serpentinization and the granite, which he considers to be intrusive into the ultrabasics. At the granite contact completely serpentinized dunite occurs. Away from the contact the serpentinization decreases and eventually unaltered dunite is found. Working on the Bomvu Iron deposits in Swaziland, Urie (1958, p.40) has found, however, that remnants of olivine in the serpentinite increased as the granite was approached! He considers this to be due to the metamorphic effect of the granite on the serpentinite. Serpentinization of the dunite and peridotite of the Great Dyke of Rhodesia is considered by Worst (1958) to be related to depth below surface and, although this is not clearly stated, it would appear that van Eeden and

his co-workers (1956) hold a similar view on the serpentinites of the Barberton area. The author has found, however, that in the latter area remnants of olivine are rather scarce in the serpentinite and it would be difficult to reach a definite conclusion on its relationship to dunite. At the Havelock Mine remnants of olivine grains were found in serpentinite on 4th Level, while the serpentinite on 5th Level (150 feet deeper) contained no olivine at all.

Two types of serpentinite occur in the Barberton area – a light green and a blue-green variety. As has been pointed out earlier, Hall (1930) as well as van Eeden (1956) are of the opinion that they represent original dunite and pyroxenite respectively. In some cases, as at Amianthus and Munnik Myburgh Mines, the contact between the two types of serpentinite is sharp, while in others, as at Havelock, the light green serpentinite grades upwards into the darker variety. The blue-green variety is considered by some to be intrusive into the lighter green serpentinite (van Eeden et al., 1956, p.116). At Stolzburg Mine the blue-green variety is found as cores in the centre of the so-called "boulders", surrounded by lighter green serpentinite.

At Havelock it was also found that the serpentinites may grade along strike into talc and chlorite schist. Urie (1958, p.45) describes a case from an area south of Havelock where serpentinite, occurring between massive chert, exists in a position formerly occupied by shale. No sign of distension or disturbance of the chert was noticed and he explains the phenomenon by stoping and assimilation.

The author has found that throughout the area under discussion extreme faulting has often obscured the true relationships of the serpentinite to country rock. A case north of Barberton, where ultrabasic rocks apparently cut across sediments of the Moodies System, is also considered by van Eeden and his co-workers (1956, p.118) to be due to faulting.

In the Barberton area the basic rocks of the Jamestown Complex normally occupy a position between the Archaean granite and the sediments of the Swaziland and Moodies Systems. This is clearly seen from the map of the general geology of the area, (Appendix 1).

Contact metamorphism produced by the intrusion of the ultrabasic rocks in the Barberton area has been greatly obscured by subsequent processes. Van Eeden and his collaborators (1956, p.157), however, mention a few localities where such metamorphism was noticed. It consisted mainly of silicification of the surrounding rocks, but at some places chloritoid and andalusite were observed.

b) Origin:

It is generally accepted that the dunites and peridotites from which the serpentinites have been derived were intrusive rocks. The author would like to point out, however, that the possibility of the existence of ultrabasic magma is still a much debated problem. Bowen (1928, p.166) has found that inclusions in perdiotite indicate a temperature which would be too low for the ultrabasic rock to have been in the liquid state. He then puts forward the theory that the olivine rocks must have originated by the separation of early olivine from a basaltic magma by means of gravitative differentiation. Rafts of olivine crystals, aided by a small amount of interstitial basaltic magma as lubricant, would then be able to form intrusive bodies. According to Bowen such a process explains all the observed facts, especially the non-existence of ultrabasic lavas, the rare occurrence of peridotite, the small volume of such bodies, and the low grade of metamorphism associated with them.

Daly (1933, p.551) supports Bowen's ideas, but suggests the peridotite-substratum as a possible alternative source for olivine rocks. This view has since also been

expressed by several other geologists, e.g. Wager, Barth and Umbgrove.

The fact that ultrabasic rocks are only associated with the initial magmatic stage of an orogenesis is explained by Umbgrove (1947, p.81) as being due to (a) insufficient low-melting material being left after the first downwarp; (b) the melting of the ultrabasic rock sealing the sediments against further intrusion; and (c) the first down-buckle penetrating deepest and tapping the ~~perdiotite~~ peridotite layer while later syntectonic and post-tectonic phases only reach the basaltic layer. He suggests that the age of a serpentine belt would fix the age of the first great downwarp. De Sitter (1956, p.363) also considers the conditions existing at the start of an orogenic phase as the most suitable for the melting of rocks.

Harker, and later Hess, (1933, p.652) suggested that volatiles, mainly in the form of water may lower the melting point of olivine sufficiently for true ultrabasic magma to exist. Hess also put forward the idea that the impact on the peridotite layer by the first great down-buckle of the granite crust during an orogenesis would cause differential fusion of the olivine rock with the production of ultrabasic magma. Laboratory experiments carried out by Bowen and Tuttle (1949) have shown, however, that pure magnesian olivine will not melt below $1000^{\circ}C$ even if the vapour pressure is as high as 15,000 psi. If one accepts the laboratory evidence the theories of Hess must be considered to be untenable, in spite of the fact that they explain many of the observed field features of ultrabasic rocks.

Cooke (1937 p.65) feels that, in spite of Bowen's objections, evidence from the Thetford area, Canada, points to an intrusive nature for both peridotite and pyroxenite.

The presence of flow textures, the linear arrangement of chromite and pyroxene grains, the distribution of peridotite at the bottom and pyroxenite at the top, the narrow dykes of pyroxenite, the xenoliths of gabbro in the pyroxenite and the veins of pyroxenite in the gabbro, in his opinion, all point to a fluid magma rather than Bowen's crystal mush.

Cooke (1937, p.68) also supports the view held by Hess that a large amount of water was present in the magma and that it was this water which caused the serpentinization. Keep (1929, p.82) on the other hand has come to the conclusion that in the Rhodesian asbestos fields the serpentinization of the dunite was due to siliceous magmatic waters derived from the adjacent granite. The same view was held by Hall (1930, p.241) on the serpentinites of the Eastern Transvaal.

In her writings on the origin of granite Doris Reynolds (1947, p.205) suggested that the elements Ca, Mg and Fe are "pushed" out in front of the granitizing solutions and that these "unwanted" elements could basify the surrounding rocks (basic front). This basification could in extreme cases lead to undersaturated rocks like peridotites.

Other authors have also suggested a metasomatic origin for the ultrabasic rocks. Ramberg (1953, p.262) puts forward the view that olivine- and pyroxene-bearing rocks in granodiorite complexes could form from the latter either by subtraction of granitic material or by addition of non-granitic material. Certain dunites in Greenland are considered by him to have formed from amphibolite by Ca, Al, Na and Si extraction. Ramberg also mentions that several authors have described examples where dunitic bodies have originated by Mg-metasomatism of limestone and dolomite. The association of ultrabasic rocks with calc-silicates (Turner and Verhoogen, 1951, p.242) would lend support to his theory.

S. van Biljon (1949, p.113) has also shown that there

exists an inverse relationship between Ca and Mg in limestones, serpentinites, and dunites. From this he concludes that certain ultrabasic rocks of the Bushveld Complex have formed by progressive Mg-metasomatism of limestone belonging to the Pretoria Series of the Transvaal System.

By studying the mineralogical and geochemical relationships Avias (1955) has come to the conclusion that the serpentinites and peridotites of New Caledonia have been formed from volcanic rocks by Mg-metasomatism.
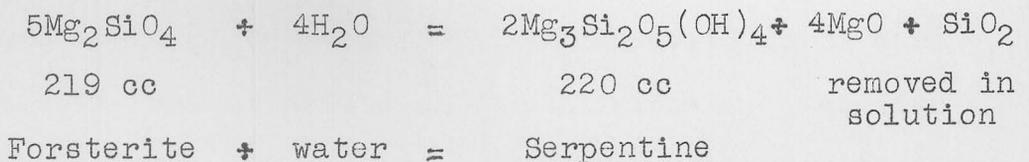
During their experiments with the $MgO - SiO_2 - H_2O$ system Bowen and Tuttle (1949) noticed a transfer of SiO_2 from the charges by means of the water vapour. This has lead them to suggest that small dunitic dykes or pipes could have formed from pyroxenite through the leaching of SiO_2 by steam passing through a crack or vent in the latter rock. Similarly steam charged with SiO_2 could change an olivine-bearing rock into a pyroxenite.

Serpentinization of olivine

Several equations have already been suggested for the alteration of olivine to serpentine. Field evidence indicates that the process takes place without appreciable increase in volume. Since a considerable amount of water is necessary for the transformation, two possibilities exist. Firstly, the water was initially present in the magma as suggested by Hess. It has already been pointed out that this process of auto-metasomatism is untenable in the light of laboratory evidence. Secondly, if the ultrabasic is considered to consist of olivine crystals with interstitial magmatic liquid, the water necessary for the serpentinization must be derived from an outside source and considerable material transfer should then take place. Three sources

for such water have been suggested by Turner and Verhoogen (1951, p.251).   When serpentinization is limited and incomplete it is probable that the water was contained in the interstitial magma and the process therefore auto-metasomatic.   If field evidence indicates a definite relationship between serpentinization and intrusives (especially granite) then the water may have been derived from such an intrusive.   Most serpentinites occur in zones of dislocation and in close association with geosynclinal sediments.   The vapour pressure of the ultrabasics will be lower than that of the sediments, and water would tend to migrate towards the intrusive thus causing serpentinization.   The absence of metamorphism around ultrabasic rocks has also been explained in this way (Hess, 1933, p.652).   Turner and Verhoogen consider a process of serpentinization in which water is derived from such sediments as the most satisfactory in the light of our present day knowledge. No mention is made by them of material transfer, but it is quite obvious that if the replacement should take place without appreciable change in volume, a large amount of material, mainly Mg, will simultaneously migrate towards the sediments causing extensive Mg-metasomatism.
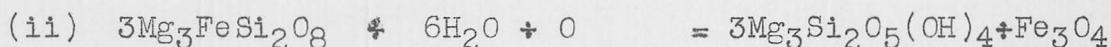
The following equation, as given by Turner and Verhoogen (1951, p.250), appears to be the most satisfactory:

$$5Mg_2SiO_4 \; + \; 4H_2O \; = \; 2Mg_3Si_2O_5(OH)_4 + 4MgO + SiO_2$$

219 cc		220 cc	removed in solution
Forsterite	+ water =	Serpentine	

Cooke (1937, p.67) suggested the following two equations as the most probable reactions:

(i) $MgSiO_3 + Mg_2SiO_4 + H_2O = Mg_3Si_2O_5(OH)_4$

Enstatite + Forsterite + water = Serpentine

(ii) $3Mg_3FeSi_2O_8 + 6H_2O + O = 3Mg_3Si_2O_5(OH)_4 + Fe_3O_4$

Fe-bearing forsterite + water = Serpentine + Magnetite

Since both these reactions involve a considerable increase in volume, they will only be possible if a certain amount of serpentine is removed in solution.   Some evidence of serpentine in veinlets within the country rock has been found, e.g. the chrysotile in the hangingwall sill at the Amianthus Mine;   it is thus possible that the above reactions do take place to limited extent.   At the Havelock Mine brucite occurs in serpentinite at several localities and the following reaction has therefore probably taken place:

$2Mg_2SiO_4 + 3H_2O = Mg_3Si_2O_5(OH)_4 + Mg(OH)_2$
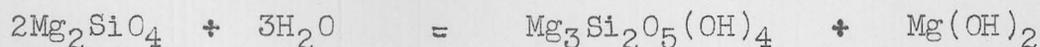
Forsterite + water = Serpentine + brucite

Again a certain amount of material must have been removed if the volume is to remain constant.

Up to now only water of deepseated origin, inclusive of connate water present in deeply downfolded geosynclinal sediments, has been considered.   From the literature it would appear that in most cases serpentinization is not clearly related to the land surface or the water table (Turner and Verhoogen, 1957, p.248).   Worst (1958), however, considers the serpentinization of the basal dunitic rocks of the Great Dyke of Rhodesia to be due to meteoric waters acting on the ultrabasic after its consolidation.   He adduces as evidence the fact that in the Wedza borehole no serpentine or water was found below 1000 feet, except along fault planes.   There is a gradual transition from serpentinite at the surface through partly altered dunite to fresh dunite in depth.

At Shabani, Southern Rhodesia, unaltered dunite occurs
at surface.   Closer to the granite, however, a borehole
has proved the existence of serpentinite and chrysotile
asbestos down to a depth of over 2000 feet.   It is rather
unlikely that meteoric water could have had an effect to
such great depths.   Furthermore meteoric waters usually
contain carbonic acid and it is therefore to be expected
that magnesite would form as a by-product of serpentinization,
according to the equation:

$$2Mg_2SiO_4 + CO_2 + 2H_2O = Mg_3Si_2O_5(OH)_4 + MgCO_3$$

Forsterite   Serpentine   + magnesite

From the depth to which magnesite occurs in the
Eastern Transvaal it would appear that the action of
meteoric water is restricted to a few hundred feet from
surface.

Different types of serpentinite

In the Barberton area two types of serpentinite are
encountered, a light green granular variety and a dense
blue-green variety.   As already pointed out, they are
considered to form from olivine-bearing and pyroxene-
bearing rocks respectively.   In the Kaapsehoop area the
contact between the two types is sharp, a fact which,
according to van Eeden and his co-workers (1956, p.116),
is due to the intrusive relationship of the original
pyroxenite.   At the Havelock Mine, however, the two
types grade into one another, the lighter green variety
at the bottom passing upwards into the blue-green
variety.   This seems more compatible with differentiation
and settling of early olivine crystals under the influence
of gravity than with separate intrusion.

The "boulder formation" occurring at the Stolzburg
Mine can hardly be explained by either of the above
processes.   The serpentinite here is traversed by a

series of joints and small faults along the contact of a pyroxenite dyke. In the centre of the blocks, defined by the joints, blue-green serpentinite occurs as oval boulders, surrounded by lighter green serpentinite carrying concentric shells of chrysotile asbestos (Plate 10). From the chemical investigation (page 78) there can be little doubt that the two types of serpentinite have been derived from the same parent rock by selective diffusion of certain elements.

Metamorphism by ultrabasic rocks

The low grade of metamorphism produced by ultrabasic rocks is a well known fact and has been explained by Bowen by means of his "cold intrusion" theory. The migration of water from the sediments towards the ultrabasic, due to a lower vapour pressure in the latter, has also been suggested as an explanation of the low grade of metamorphism (Hess, 1933, p.652). In the Barberton area the rocks of the Swaziland and Moodies Systems have similarly undergone low grade metamorphism, seldom higher than the greenschist or epidote-amphibolite facies. Only at a few isolated localities were rocks of a higher grade encountered.

Read (1951, p.14) in discussing the granitization of the rocks in the Barberton area considers the low grade of metamorphism of the sediments to be due to the protective barrier of ultrabasic rocks which occurs between the granite and the sediments. He does not deal with the metamorphism produced by the ultrabasics themselves.

To the present author this explanation is not entirely satisfactory. If it were a fact that the ultrabasic rocks were intruded into the Swaziland and Moodies Systems in sill-like fashion, they should be essentially an integral part of the sequence and have a distribution generally similar to that of the sediments.

In that case the intense folding should have revealed
bodies of the intrusives within the central portion of
the Barberton Mountain Land.   In fact, however, the
basic rocks of the Jamestown Complex are confined almost
entirely to the periphery of the sediments, thus
occupying a position between the Archaean granite and the
Swaziland and Moodies rocks.   This situation is more
suggestive of a genetic relationship between the granites
and the ultrabasic rocks themselves.

Furthermore the ultrabasic rocks also surround the
Kaap Valley Granite which is considered by Read to be of
magmatic origin.   In the latter case the "basic resistor"
theory cannot be applied and doubt is cast on its
applicability to the Archaean granite-gneiss.

The metamorphism of the Jamestown rocks by the
Nelspruit granite is, according to van Eeden and his
co-workers, (1956, p.154), mainly of a dynamic nature.
Thermal metamorphism is restricted to the zone immediately
in contact with the granite.   Urie (1958, p.45) has
described the increase of olivine remnants in serpentinite
when the granite is approached, and has attributed this
to the metamorphic effect of the granite.

Yoder (1951) studied experimentally the system
$MgO - Al_2O_3 - SiO_2 - H_2O$ and arrived at the conclusion
that pressure (hydrostatic as well as stress) plays a
minor role in metamorphic reactions.   He feels that
temperature and chemical composition are the controlling
factors.   Furthermore, he found that water vapour
pressure has a very important effect on the stability of
minerals.   In an environment of excess water vapour
"low grade" minerals may remain stable to temperatures
higher than normally accepted and, similarly, "high
grade" minerals, in absence of water vapour, may appear
at temperatures well below those at which they would have
formed with a higher vapour pressure.

Structural control is also emphasized by Yoder (1951, p.619) because in disturbed areas water will have greater access, and the grade of metamorphism will be lower than in areas where access of water is restricted. The low grade of metamorphism found at certain granite contacts is considered by Yoder to be due to the presence of excess water vapour.

This explanation can well be applied to the rocks of the Barberton area. No matter whether one considers the Nelspruit granite as of magmatic or metasomatic origin it is obvious that during its emplacement water must have been driven out of the invaded rocks. This water would accumulate in the remaining sediments, which would then be able to resist metamorphism or granitization longer than if they were deficient in water vapour. The low grade of metamorphism exhibited by the serpentinite can be explained in a similar manner.

Note on the origin of the Serpentinite
of the Jamestown Complex

The serpentinite of the Jamestown Complex could in general be considered to be of the Alpine type. Its occurrence as lenses and concordant sills, associated with cherts, in a highly folded region is in agreement with the nature of serpentinite from many other localities in the world. From the afore-going discussion it could then be concluded that the sills were probably emplaced as a crystal mush consisting of olivine with a small amount of interstitial magma during the initial downwarp of the orogenic period in which the rocks of the Fig Tree Series were folded. On cooling, serpentinization of the dunite and peridotite took place mainly as a result of water migrating from the invaded sediments towards the ultra-basic rocks.

It should be pointed out, however, that certain features of the serpentinites would be difficult to explain by means of this theory.

(a) The gradation of light green serpentinite (derived from dunite) into blue-green serpentinite (derived from pyroxenite), which exists at the Havelock Mine, points to gravitative differentiation.   This process could hardly have taken place in a crystal mush and would indicate a more fluid magma.   On the other hand, the existence of a fluid magma is unlikely in view of the experiments of Bowen and Tuttle (1949).   Diffusion of material during metamorphism could be a possible explanation.

(b) The field relationships of the basic rocks of the Jamestown Complex (i.e. their occurrence between the granite and the sediments) would, as was pointed out before, indicate to the present author a genetic relationship between the granite and the ultrabasic.   Doris Reynolds' "basic front" theory may offer a solution.

(c) The relationship between certain sediments and the serpentinites also poses difficulties for a magmatic theory.   Many examples exist where serpentinite, occupying a position between chert bands, grades along strike into argillaceous rocks. To explain the "disappearance" of the shale by means of the "crystal raft" intrusion would be well nigh impossible.   If a more liquid magma is envisaged a complicated process of stoping, assimilation, and differentiation has to be invoked. Would a metasomatic origin for the serpentinite here not be more acceptable?

Since this thesis is mainly concerned with the origin of chrysotile asbestos, and not with the origin of serpentinite, the problem could not be fully investigated. A detailed field investigation coupled with geochemical and trace-element studies should yield interesting information which may lead to the solution of this fascinating problem.

B. CHRYSOTILE ASBESTOS

1. Nature of chrysotile veins in serpentinized dolomite

Seams of high grade chrysotile asbestos, varying in length from a fraction of an inch to over 6 inches, occur at isolated localities in serpentinized dolomite. The best fibre is associated with zones of resinous, green or honey-coloured serpentine but good fibre may also occur in partly serpentinized dolomite, that is, in a rock consisting of calcite with disseminated serpentinite. The fibre seams are usually parallel to the bedding of the dolomite except in the case of some dykes where the seams are arranged parallel to the walls of the dyke. The seams are usually straight with parallel edges but occasionally veins which bend or bifurcate are found. In such cases the fibres are all orientated in the same direction and need not be perpendicular to the walls of the vein (Plate 48). Lenticular seams, often arranged en echelon, are also not uncommon.

Along strike a seam may peter out over a short distance with another seam starting at a slightly different horizon. In rare cases a single seam could persist for several tens of feet. Often a seam of long fibre will peter out altogether leaving only a zone of serpentinized dolomite with stringers of short fibre. Some distance further on the long fibre may appear again.

This erratic distribution of long fibre makes the estimation of ore reserves of chrysotile asbestos in dolomite extremely difficult.

It is a well known fact that serpentinized dolomite can exist for long distances along the contact of basic sills but that chrysotile asbestos is only locally developed. From the investigation of the asbestos deposits in the dolomite the author has found that chrysotile fibre only occurs where the serpentinized dolomite has been disturbed by subsequent faulting or dyke intrusion. In most cases fibre has been worked on one side only of such a fault or dyke although a few examples are known where asbestos occurs on both sides.

Normally the fibre is silky and of a high quality but in some cases, talcification has taken place. With the first appearance of talc the fibre is still soft but loses its tensile strength. When it becomes completely talcified the fibre is hard and brittle. The talcification may begin from the edges of a vein or from partings running through the fibre (Plate 49). Although not definitely established it would appear as if the areas of talcified fibre are restricted to the vicinity of the main fault or in some cases of smaller subsidiary faults. Thin coatings of calcite have also been observed on the fibres. The tensile strength in such cases is still high but the fibres become harsh and springy. No magnetite was noticed with any fibre in serpentinized dolomite.

2. Nature of chrysotile asbestos in massive serpentinite

Veins of chrysotile asbestos in massive light green serpentinite may occur in two ways: (a) a large number of parallel seams known as "ribbon" fibre, and (b) veins following a fracture pattern spread more or less uniformly

throughout a serpentinite body, forming a "stockwork" of fibre.

Seams of "ribbon" fibre are usually parallel to the contact between the serpentinite and rocks of different physical properties; for example, dense blue-green serpentinite at the Munnik Myburgh Mine or Godwan quartzite at the Amianthus Mine.   The zone of fibre-bearing rock is seldom more than a few feet wide and may be known as a "reef", a "lode" or a "line".   The number of parallel seams may vary from only a few to as many as 30 seams per linear foot over several feet (Hall, 1929, p.118).   In most cases the majority of the seams are very thin with only one or two veins of longer fibre. Although the fibre-zone may be continuous for several hundred feet, individual fibre seams usually peter out over short distances with new seams starting again at a slightly different horizon (Fig.5B).   Single seams may also split or branch to join other seams but only in a few cases was one seam seen to cut another (Fig.2). The fibre usually adheres more strongly to one wall than to the other (Cooke, 1936, p.93 and Riordon, 1955, p.68). In the seams with longer fibre, partings are often present. They may consist merely of a break in the fibre or may be filled with apple-green serpentinite or grains of magnetite. The partings are usually parallel to the walls of the vein but examples of partings cutting obliquely across the seam can also be found.   Seams without partings are called one-fibre veins and those with a parting two-fibre veins (Cooke, 1936, p.92).

In the case of a stockwork, veins of chrysotile traverse the whole serpentinite body.   Although the distribution of the seams may appear to be at random it can usually be established that they follow a fracture pattern in which there is a certain amount of orientation (Plate 5).   This orientation is, however, of a regional

nature and a particular set of veins may exist only for a small distance. Further away it may be found that the fibre seams are orientated according to a different pattern. As in "ribbon" type fibre, the veins of a "stockwork" are restricted to light green serpentinite and peter out when the blue-green variety is approached. The average length of the fibre of the "stockwork" type is usually greater than that of "ribbon" fibre but individual seams of the latter may be longer. The longest fibre encountered in a deposit of the stockwork type was one seam of $2\frac{1}{2}$ inches on 4th Level, Havelock Mine.

The "boulder" formation, such as that found in the Stolzburg Mine, can be considered to be composed both of "ribbon" fibre and of a "stockwork". The chrysotile seams of the "ribbon" type are here orientated parallel to the contact between the dark green serpentinite in the centre of the boulder and the lighter green variety which forms the rim. The zones of "ribbon" fibre resemble a "stockwork" (Fig.3 and Plate 10). Partings are commonly found and are similar to those occurring in "ribbon" fibre. The fibre is usually orientated perpendicular to the walls, but where seams curve or bend the fibre often retains the same orientation and is then at an angle to the walls. Irregularities in the wall rock on opposite sides of a vein can usually be fitted into one another. The direction of the fibres then corresponds to the direction of the movement. In such a case the width of the seam may vary but the fibre length remains constant (Plate 21).

Particular attention was paid to junction of veins. In most cases fibre seams peter out where they meet one another, often with development of apple green compact serpentine (picrolite) at the junction. In other cases the asbestos veins curve round and change direction when two veins join, (Fig.13). Occasionally magnetite as well as

magnesite occurs at the junction of seams. Only rarely were two seams seen to cross one another. Cooke (1936, p.96) observed similar features in the Canadian asbestos deposits.

In most chrysotile veins the fibres are straight but in a few cases bends were noticed (Fig.14A). These are readily seen when the fibre is observed in reflected light. An unusual example of this bending was encountered at the Havelock Mine where one seam consisted of curved fibre (Fig.14B). It appeared to be the result of a great number of bends which were closely spaced. The fibre was strong and did not break at the bends. Slip fibre would be an extreme case of bending where the fibres are orientated parallel to the walls.

The wall rock of chrysotile asbestos is usually the light green granular serpentinite. At the Amianthus Mine irregular zones of brown serpentinite occur and it was noticed that chrysotile seams petered out when entering the latter (Fig.2 and Plate 46). At the Havelock Mine discoloured zones exist on either side of some asbestos veins. Dresser (1913) stated that in the Thetford area a constant ratio of 1 : 6.6 exists between the length of the fibre and the width of the altered zone. This has been shown not to be the case, for the altered zones continued after the fibre had petered out (Cooke, 1936, p.103). Although fibre normally occurs in serpentinite, examples of chrysotile existing in diabase have been found e.g. at the New Amianthus Mine and the Elandshoek Mine.

In many cases chrysotile seams have a thin layer of dense apple-green serpentine (picrolite) separating them from the granular serpentinite. At the Munnik Myburgh Mine, the "Griffin" line often contains zones of the dense light green serpentine with branching veinlets of chrysotile asbestos (Plate 44). This dense serpentine

is isotropic under the microscope and resembles material
formed from colloidal suspension.   Similar material
(Specimen V.119) from the Havelock Mine consists of short
chrysotile needles, as shown by the electron microscope.
Along strike this material grades into chrysotile.

3.   The cause of brittleness
of chrysotile asbestos

It has been found that the main cause of
deterioration of fibre-quality is the replacement of
chrysotile by talc, that is, an increase in the percentage
silica and a decrease in the amounts of magnesia and
water.   An extremely small amount of talc admixed with
fibre may give the fibre a soft talcy feel and may even
be beneficial to the quality.   With increased
talcification the fibre remains soft but loses its
tensile strength.   When completely talcified the fibre
is hard and brittle.   Keep (1929, p.107) has also found
that brittle fibre normally has less water than high
quality fibre, which is thought to be due to the presence
of talc.   Similarly it was found that the high quality
fibre from the Thetford area had a higher magnesia and
water and a lower silica and iron content than harsher
fibre from the Vimy Ridge area (Cooke, 1937, p.134).

Soboleff and Taraninoff (1933) have investigated
the problem of brittle chrysotile and have also come to
the conclusion that the presence of talc is the cause of
the brittleness.   The chemical analysis of brittle
fibre from Havelock Mine (Specimen V.123) showed a
relatively high percentage of Ca.   This Ca, however,
is present in the form of a carbonate and does exist as
an isomorphous replacement of Mg as suggested by
previous authors.   Similarly harsh fibre from the
Congo-Vaal Mine was found to contain coatings of calcite.

Isotropic material noticed in a thin section of brittle fibre (Specimen V.123) from Havelock Mine may be opal, since the chemical analysis indicated a relatively high percentage of both silica and water.

Deterioration of fibre as a result of the intrusion of younger dykes has also been found to be the result of talcification in most cases. Spoilt fibre from Havelock Mine (Specimen V.126, Plate 30) was seen to consist of secondary serpentine growing at right angles to the original fibre direction. This could have been caused by tension acting in a direction perpendicular to the direction of the fibres. Brittle fibre (Specimen V.137) occurring in "chocolate" serpentinite next to a dyke at the Havelock Mine was found to have been recrystallized to a fine aggregate and radiating bundles of serpentine (Plate 31). It would appear as if the chrysotile has been changed into antigorite. This could be the result of the introduction of Al and Fe from the intrusion.

Complete replacement of chrysotile by other minerals also occurs. At the Sunnyside Mine crossfibre veins consisting mainly of magnetite with interstitial serpentine were found. Slip fibre replaced by magnetite also occurs. At the Amianthus Mine, barbertonite and stichtite have replaced thin veinlets of chrysotile and at Havelock Mine a vein of fibrous magnesite was seen to grade into chrysotile asbestos. Veins of opal associated with chrysotile and magnetite at the Doyershoek Mine appear to be cavity fillings and not a replacement of fibre.

4. The Origin of Chrysotile Asbestos

(a) The fibrous growth

Much has already been written on the way in which chrysotile fibres are supposed to have formed. Three possible modes of growth may be considered.

Firstly the chrysotile fibres could have grown in open cavities. One would then expect that the growth would take place from both sides and that chrysotile should always have a parting where the fibres meet. With such an origin it would also not be necessary for the fibres growing from the two sides to have the same orientation, a condition which is in contradiction to observed features. Furthermore, if account is taken of the great number of parallel seams of the "ribbon" type as, for instance, at the Amianthus Mine, it is very unlikely, if not impossible, that so many open spaces could have existed.

A second possible mode of formation could be that the fibre grew at the expense of the wall rocks, that is, replacing the serpentinite durings its growth (Dresser, 1913 and Graham, 1917 and 1944). In the light of evidence from the present area, however, a replacement origin for most fibre appears to be untenable. A characteristic of veins which have originated by replacement is the irregularity of their walls. Thin veins of chrysotile in most cases have walls which are parallel to one another and irregularities on one side usually fit into those of the other side. If this feature is to be explained by replacement one would have to visualize an equal rate of growth all along the vein, a process which is rather unlikely. In the case of veins with longer fibre the irregularities in opposite walls can very often not be matched and a certain amount of replacement must have taken place. Chrysotile veins are also found in rocks other than serpentinite, for example, in diabase at the Amianthus Mine. This would indicate that at least some seams of chrysotile must have crystallized entirely from solution. In a few cases irregular veins of chrysotile exist in dense apple-green serpentine (picrolite)

Their habit is best explained by replacement (Plate 44).

The third possible mode of formation is that the fibre grew in fractures either by pushing the walls apart (Taber, 1916, 1917, 1924 and 1926) or during the gradual separation of the walls of the fractures under the influences of other forces (Keith and Bain, 1932, Keep, 1929 and Cooke, 1937). Riordon (1955, p.77) has come to the conclusion that fissure filling is normally the main process, with perhaps a small amount of replacement along the edges of the seams. He states, however, that under special conditions one or the other process may predominate. Furthermore, Riordon (1955, p.80) has suggested that initially picrolite formed in the fractures and that chrysotile resulted through recrystallization from this picrolite. Evidence from the present area supports the findings of Riordon as far as the gradual opening of the fractures and the small amount of replacement are concerned. It is felt, however, that the chrysotile fibres actually grew during the separation of the walls of the fractures and not as a recrystallization of picrolite. This statement will be discussed further on.

(b) <u>The stability of antigorite and chrysotile</u>

Pauling (1930) predicted that the layered structure of antigorite would be unstable and would tend to curve. Later it was suggested that isomorphous replacement of Mg by Fe or Al could stabilize the structure (Bates and Mink, 1950). This view was supported by Yoder (1952, p.579) on the strength of laboratory evidence. The results of the present investigation have also indicated that serpentinite which consists of antigorite usually contains a higher percentage Al and Fe than does chrysotile.

Turkevich and Hillier (1949) as well as Bates, Sand and Mink (1950) have shown that chrysotile asbestos has a tubular structure. It is therefore clear that when no

Al or Fe is present, chrysotile would be the stable mineral but that, in the presence of these elements, antigorite may be more stable. Experimentally Nagy and Bates (1952) have found that antigorite was less soluble in HCl than chrysotile and also that it was more stable thermally. On the other hand, synthetic chrysotile is readily prepared but antigorite has only been synthesized in the presence of aluminium (Yoder, 1952, p.579). It is also quite clear that under conditions of tension, chrysotile, with its fibrous habit, will be favoured whereas platy antigorite may be more stable under shearing stress.

Fe-antigorite and Fe-chrysotile are relatively scarce and therefore considered to be unimportant in the present discussion. A continuous series between antigorite and the chlorites was suggested by Winchell (1951) but Yoder (1952) feels that although a solid solution series may exist between antigorite and clinochlore the suggestion with regards to the rest of the chlorites is not well founded.

(c) The relationship of dense apple-green serpentinite (picrolite) to chrysotile

Dense apple-green serpentinite is found closely associated with most veins of chrysotile asbestos. Either it forms a thin layer separating the fibre from the wall rock (granular serpentinite, serpentinized dolomite or even calcite-serpentine rock) or it occurs as fragments in the fibre and along partings. At junctions of fibre seams it is nearly always present and at a few localities veins of dense green serpentinite were seen to grade into chrysotile along the vein. Dense apple-green serpentinite also occurs on some shear planes.

Under the microscope the serpentinite appears isotropic or nearly so (Plate 34). Birefringent patches

or thin veinlets may occur locally in the serpentinite.
Occasionally a banded structure is present often with thin
veinlets of chrysotile parallel to the banding (Plate 37).

The chemical analysis of dense apple-green serpentinite
(Specimen V.119) shows a relatively high percentage of Al
and Fe^{+++}.   By comparison with the massive serpentinite
one would therefore expect the former to be composed of
antigorite rather than chrysotile.   Under the electron
microscope, however, it can be seen that the rock consists
of short tubular fibres of chrysotile (Plate 52).   The
relatively high content of Fe^{+++} and Al could possibly be
accounted for by the presence of large grains of magnetite
which are seen in thin section.   Several of the magnetite
grains show well defined crystal faces which might suggest
that they crystallized before the serpentinite became
completely solid.

Riordon (1955, p.79) reached the conclusion that the
formation of chrysotile took place in two stages.   During
the first stage picrolite crystallized from serpentinous
solutions and during the second stage chrysotile formed
by recrystallization of the picrolite.   This view is
supported by a suggestion of Bowen and Tuttle (1949)
that chrysotile will form only by recrystallization.
On the other hand Jagodinski and Kunze have come to
exactly the opposite conclusion, namely that chrysotile
fibre will only grow from a watery solution.

If Riordon is correct in supposing that all chrysotile
recrystallized from picrolite the present author feels
that more examples should have been found representing
the intermediate stages, that is, picrolite in the
process of changing to chrysotile.   In nature, however,
picrolite is in most cases confined to thin layers
between fibre seams and wall rock, to inclusions along
partings and to the junctions of seams.   Veins of
picrolite changing into chrysotile are very scarce.

Fibre seams and picrolite are both composed of the same mineral, chrysotile. This would indicate that the difference between them does not lie in the crystal structure (Riordon assumed that picrolite had a flaky habit) but more likely in differing conditions during crystallization. It is a well known fact that fibrous growth in minerals is promoted by conditions of tension. The author would like to suggest that chrysotile crystallized directly from serpentinous solutions under tension while picrolite represents material which remained after the tension was released or crystallized at places where no tension existed. This would explain the existence of thin layers of picrolite between the fibre and wall rock, the occurrence along partings and the presence of picrolite at the junction of seams.

(d) Structural control

Most previous authors have recognized the fact that veins of chrysotile asbestos occur in fractures or joints which formed in the serpentinite as a result of external forces. Most of these authors, however, also consider these fractures to have acted merely as passages for watery solutions to enter the serpentinite. The actual formation of chrysotile fibre is then attributed to these solutions. In the Rhodesian fields the fractures are considered to be due to contraction of the ultrabasic body on cooling (Keep, 1929, p.102). It is then suggested that siliceous solutions derived from the nearby granite first caused serpentinization of the dunite along these fractures and that, shortly afterwards, chrysotile crystallized in the same fractures while the walls were still moving apart. Keep (1929, p.96) mentions, however, that the jointing in the dunite is different from that in the serpentinite and explains this as due to compression and contraction respectively.

To the present author this difference in fracturing would indicate that the fractures formed after serpentinization had taken place.   The different fracture patterns are due to the effects of external forces on rocks with different physical properties.   According to Keep (1929, p.120) a large fault skirts the asbestos deposits at Shabani.   He does not consider this fault to be of any importance as far as the origin of the fibre is concerned but considers the solutions causing the talcification to be associated with it.

Cooke (1937, p.116), in discussing the Canadian deposits, recognized the association of chrysotile asbestos with faulted areas.   He states that hot solutions were able to enter the dunite, (which was already partly serpentinized by solutions contained in the original magma) along these fractures.   The new solutions then caused recrystallization of the serpentinite to chrysotile. The occurrence of deposits in the vicinity of acid intrusions, is due to the fact that the solutions were able to retain their heat longer in those areas (Cooke, 1937, p.136).

From the present investigation of deposits occuring in the Eastern Transvaal it has become clear that most of the chrysotile deposits in dolomite are intimately associated with faulting.   Faults are also evident at most of the occurrences in massive serpentinite.   At the Havelock Mine a large fault occurs in the immediate footwall of the ore-body; at the Amianthus, Munnik Myburgh and Sunnyside Mines the deposits occur in the vicinity of faults and appear to peter out away from them; at the Stolzburg Mine a well marked shear zone exists just south of the asbestos occurrences and several small faults have displaced the pyroxenite dyke; at the Kalkkloof Mine the asbestos deposit is clearly related to the dolerite fault-dyke; and at the Barberton Chrysotile

Mine the fibre deposits are found only in the area where the serpentinites abut against rocks of the Fig Tree Series.   In the serpentinite of the Great Dyke of Rhodesia chrysotile asbestos deposits are also restricted to the vicinity of faults (Worst, 1958).

This association of the chrysotile deposits with faulting could be explained in two ways.   In the first place fractures caused by the faulting could have provided channelways for watery solutions which brought about the formation of chrysotile.   This is the view held by most previous authors.   It is felt, however, that if this were the case, one would have expected to find chrysotile asbestos also along other channelways such as joints, fissures, shear planes and fractures not necessarily connected with faulting.   This, in fact, is not the case and it has been found that shear zones in fibre-bearing serpentinite are usually devoid of fibre.

On the other hand, as already mentioned, tension would promote the growth of chrysotile.   In discussing the chrysotile deposits of New South Wales, Proud and Osborne (1952) also came to the conclusion that a correct stress environment was the controlling factor in the development of fibre.   In general, tension fractures may form along certain portions of shear faults, in the tensional region of folds and, in some cases, as a result of the cooling of igneous rocks (Newhouse, 1942, p.10).   In the Eastern Transvaal folding is relatively rare and tensional fractures would therefore be produced mainly by faulting and probably also by the cooling of igneous intrusions.   The asbestos deposit occurring parallel to the sides of the dyke on Elandshoek 139 would possibly be an example of the latter.   In the case of faulting, the tension fractures are often restricted to the contact of "favourable" and "unfavourable" rock types (Newhouse, 1942, p.24).

Since many of the chrysotile deposits in the massive light green serpentinites occur along the contacts of the latter with other rocks, it would indicate to the author that here, too, tension has played an important role in the formation of the fibre.

In the case of the "boulder formation" occurring at the Stolzburg Mine, it has already been mentioned that the boulders lie at the centres of blocks outlined by a system of joints next to a pyroxenite dyke (p.28a, Figs. 3B & C). From the chemical investigations (p.78) it has been suggested that the joint systems controlled selective diffusion of certain elements which transformed the dark green serpentinite into the light green variety.   This process is analogous to spheroidal weathering in jointed basic rocks.   It is also to be expected that during the transformation, changes in volume would take place and stresses acting radially to the core could develop producing concentric fractures in a manner analogous to exfoliation.   Fibre would form in these fractures while the tension prevailed.

Similarly the volume changes involved in the complex relationship between green and brown serpentinite at the New Amianthus Mine (p.26a, Fig.2) have lead to a system of more or less radial fractures with fibre formation.

From the above discussion it will be clear that the age of fracturing would also be the age of fibre formation. In most cases there is no direct means of determining the age of asbestos deposits.   Faults, however, can quite often be dated by stratigraphic criteria.   For example, in the Kaapsehoop area the asbestos deposit of New Amianthus Mine is clearly post-Godwan in age.   On the other hand, the fibre horizons at the Munnik Myburgh Mine appear to be related to the folding of the Jamestown basic rocks which are pre-Godwan.   If it is understood, however, that the fibre formation at the latter mine was

controlled by post-Godwan, pre-Transvaal faulting, it is possible that the chrysotile deposits of this area all belong to the same period of structural deformation. In the same way it can be inferred that the chrysotile deposit of the Kalkkloof Mine must have formed during Karroo times.

(e) The serpentinous solution

It is generally accepted that a solution of some sort must have aided the recrystallization of serpentinite into chrysotile. These solutions are considered by most previous authors to have been hot and derived from acid or basic intrusions (hydrothermal solutions). Hall (1929, p.248), however, has expressed the view that the formation of chrysotile asbestos is due to the action of meteoric rather than magmatic waters. This theory was based on the fact that many asbestos occurrences appeared to peter out in depth. Worst (1958) has come to similar conclusions on the asbestos occurrences of the Great Dyke. At Shabani chrysotile has been proved by drilling to exist down to a depth of over 2000 feet. Normally meteoric water is restricted to a depth of approximately 1000 feet but instances are known where "underground" water occurred down to depths of several thousand feet. It is thus impossible, even in the deepest deposits, to exclude either meteoric or magmatic water as the aid to asbestos formation. In the view of the present author the origin of the watery solution is not important. Tension is the controlling factor and any solution, be it magmatic, meteoric or connate would suffice.

In a rock fractured under shearing stress, tension fractures will develop in some directions but compression will be present at other points. It is suggested that the stresses in the rock will be relieved by solution of the serpentine at the points of pressure and by the

migration of the serpentinous solution to the tension fractures where chrysotile asbestos will grow in the direction of tension. From the discoloured zones found along some chrysotile seams it would appear as if migration of material towards the fracture may also take place. A certain amount of replacement of the wall rock may then be evident. In most cases the fibre grows only from one side of the fracture but in some cases growth from both walls may take place, new material being added to the ends of the fibres. A parting will then be present where the two sets of fibres join. Although the serpentinous solution probably does not travel far, it is possible that some of the solution may enter rocks other than serpentinite. This would explain the occasional existence of fibre in diabase. Whether the serpentine is in true solution or in the form of colloidal suspension is not certain. Excess material in solution, for example magnetite, will be deposited along partings or along the edges of veins.

The upper stability temperature for serpentine has been established as $500^{\circ}C$ or $450^{\circ}C$ in the presence of brucite (Bowen and Tuttle, 1949). It is therefore likely that the most favourable temperature for chrysotile formation would be of the order of $400^{\circ}C$. Chrysotile remains stable down to normal temperatures and it is thus possible that fibre can grow even in the zone of weathering, although fibre-growth would then probably be extremely slow.

It is therefore apparent that, provided the correct tensional conditions and sufficient watery solution be present, chrysotile asbestos can be expected to form at all depths at which serpentine is stable. If the temperature is too high and insufficient water is present olivine will replace serpentine and no fibre could be expected. This deduction may have important economic consequences.

CONCLUSION

It should be clear from the afore-going discussion that a wide variety of theories have been proposed to account for the origin of ultrabasic rocks and of serpentinite. None of these theories explains adequately the features observed in the area under discussion. It is suggested that a metasomatic origin for the serpentinites of the Jamestown Complex may offer a solution to the problem.

The possible origin of serpentinite is not the object of this study, which is concerned more with the origin of chrysotile asbestos.

It is also believed that fibre growth is independant of the origin of the serpentinite but merely depends on its existence.

From the laboratory investigations it is confirmed that two serpentine minerals exist - chrysotile with a fibrous habit and antigorite with a flaky habit. Under the microscope large veins of chrysotile are easily recognized but antigorite and finely disseminated chrysotile are not readily distinguished. Many massive serpentinites consist of both these minerals and the electron microscope then forms a useful tool for recognizing the flaky and fibrous minerals. Small differences in the d-spacings of the serpentine minerals have lead previous workers to suggest new varieties. From the present investigation it is clear that at least some of the differences can be accounted for by isomorphous replacements of elements in the serpentine. In the D.T.A.-curves variation in peak temperatures can be partly explained by the difference between chrysotile and antigorite while the variations in the intensities of peaks seem to be directly related to the difficulty of grinding and of packing chrysotile to a desired density.

Chrysotile asbestos deposits, both in serpentinized dolomite and in massive serpentinite, have been found to be intimately associated with faults. Previous authors have in most cases attributed fibre formation to hydrothermal solutions. Where faults were recognized, these were considered merely to have provided channelways for the solutions.

From the evidence presented, the author has come to the conclusion that major importance must be attached to tensional faults occurring after serpentinization of the country rock. Under tensional conditions the growth of chrysotile fibres is favoured and it is considered that the fibre deposits result from growth of chrysotile in tensional fractures while the tensional conditions persisted. The source of the solutions in the fractures is not regarded as of primary importance though their presence is necessary.

Siliceous and carbonated waters entering the rock along the faults could, subsequently to the formation of the fibre, cause talcification and carbonatization both of the serpentinite and of the chrysotile. This is the probable cause of "brittle fibre".

The author feels that these views on the origin for chrysotile asbestos can be applied to all the deposits examined. Whether the theory can be applied also to other deposits remains to be proved but seems to be in accord with published evidence.

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