5. The Chrysotile Deposits of the Eastern Transvaal and Swaziland

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ABSTRACT

A general survey of the geology of the Eastern Transvaal is given. The geology and nature of the chrysotile deposits both in serpentinized dolomite and massive serpentinite is described. Before dealing with the origin of serpentinite and chrysotile a brief survey of the mineralogy of the serpentine minerals is given. Different theories on the origin of ultrabasic rocks and serpentinite as well as chrysotile are discussed. It is concluded that chrysotile asbestos deposits have developed in serpentinized dolomite and serpentinite along tensional fractures produced mainly by faulting. The cause of brittleness in chrysotile asbestos is also briefly discussed.

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INTRODUCTION

Chrysotile asbestos occurs in the eastern Transvaal both in massive serpentinite and in serpentinized dolomite. Many of these deposits have been described by Hall (1930). The largest deposit, however, that of the Havelock Asbestos Mine, situated just over the border in Swaziland, has been opened up since the days of Hall and much new information has thus become available. The mineralogy of serpentine minerals is also now more clearly understood since they have been studied by means of modern methods such as X-ray diffraction, the electron microscope and Differential Thermal Analysis.

The author is of the opinion that the fibre occurring in the two widely differing rock types must have originated under essentially the same conditions.

In this paper the characteristics of the two types of deposits will be briefly described and a mode of origin proposed which, it is believed, satisfies most of the observed facts.

GENERAL GEOLOGY OF THE EASTERN TRANSVAAL

Before presenting the descriptions of the individual deposits, it is necessary to give a general survey of the geology of the eastern Transvaal as a whole (Plate I).

The Basement Formations

The oldest rocks in the area form the rugged country known as the Barberton Mountain Land. This is built up by highly folded sedimentary and low-grade metamorphic rocks which have been subdivided into the basal *Swaziland System* overlain unconformably by the *Moodies System*. The former can be split up lithologically into (*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*, comprising more than 7,000 ft. of sediments. In the Sheba Hills area the series consists of shale and chert at the base followed by green schists, talcose and carbonate rocks. These are overlain by shale, banded ironstone, graywacke, grit and conglomeratic grit followed by trachytic lava near the top of the succession (Van Eeden *et al.*, 1956, p. 55).

In the southern part of the Barberton Mountain Land the sequence had not yet been determined, mainly because of the complicated structure, poor outcrops and the absence of mining activities in rocks of this series. From an investigation by the author it would appear, however, that all the rock types are also represented in the south.

The younger *Moodies System* begins with a fairly persistent conglomerate at the base, overlain by calcareous and feldspathic quartzite followed by a large thickness of slate, phyllite and graywacke with some interbedded graywacke.

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 M'babane in Swaziland (Plate I).

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 in sill-like fashion and then by a large mass of granodiorite known as the *Kaap Valley Granite.* These intrusive rocks are collectively known as the *Jamestown Igneous Complex* (Van Eeden *et al.*, 1956 p. 112). The basic and ultrabasic rocks consist mainly of green serpentinite, blue serpentinite, diabase and basic schist.

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 derived proably from an amphibole-bearing 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. The author has found, however, 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, probably diffusion during metamorphism (W. J. van Biljon, 1959, p. 101).

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. Willemse (1937, p. 96) determined the feldspar in the rock as andesine and calls it 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 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 oligoclase (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 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 mode of 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 Godwan 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, feldspathic quartzite and shale.

The Godwan Formation is overlain by the rocks of the *Transvaal System*. 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 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 1,600 and 1,800 ft. at Pilgrim's Rest in the north to about 120 ft. 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 lies the Bevet's conglomerate composed of angular chert pebbles set in a siliceous matrix. In the southern portion of the area this 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. Both the Daspoort Stage and the Magaliesberg Stage are composed mainly of shale with quartzite near the top of the successions. Interbedded lava and tuff occur in both stages.

Basic, and in some places ultrabasic, 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 part of the 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.

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, 30^0 west of north, 30^0 east of north, and north-south. A few deviations from these directions are also found (Van Eeden *et al.*, 1956, p. 137).

THE ASBESTOS DEPOSITS

Mines Situated in Massive Serpentinite

Havelock Asbestos Mine

General. The Havelock Mine is situated in Swaziland half a mile from the Transvaal border and about 12½ miles south-southeast of the town of Barberton. It is connected to the latter by an aerial ropeway and a winding road some 25 miles long. The mine, with an elevation of 3,700 ft. at the main quarry, lies at the foot of the Emlembe mountain which rises to over 6,000 ft. A rainfall of over 90 in. per annum has caused deep weathering of most of the rocks and outcrops are usually obscured by a thick covering of soil and vegetation (Plate II (*a*) and (*b*)).

Surface geology. The rocks of the area consist mainly of chert, schist and carbonate rock belonging to the Fig Tree Series of the Swaziland System (Fig. 1). Of these, only the chert bands form prominent outcrops and can usually be found along the ridges. The other rocks are nearly all deeply weathered and are only exposed in road cuttings, mine workings and occasionally in stream beds.

The asbestos deposit occurs in a sill-like body of serpentinite belonging to the basic phase of the Jamestown Complex, conformably emplaced in massive chert and schist. The orebody strikes about east-west and is situated where the Tutusi River crosses the serpentinite (Fig. 1) which here has a surface width of

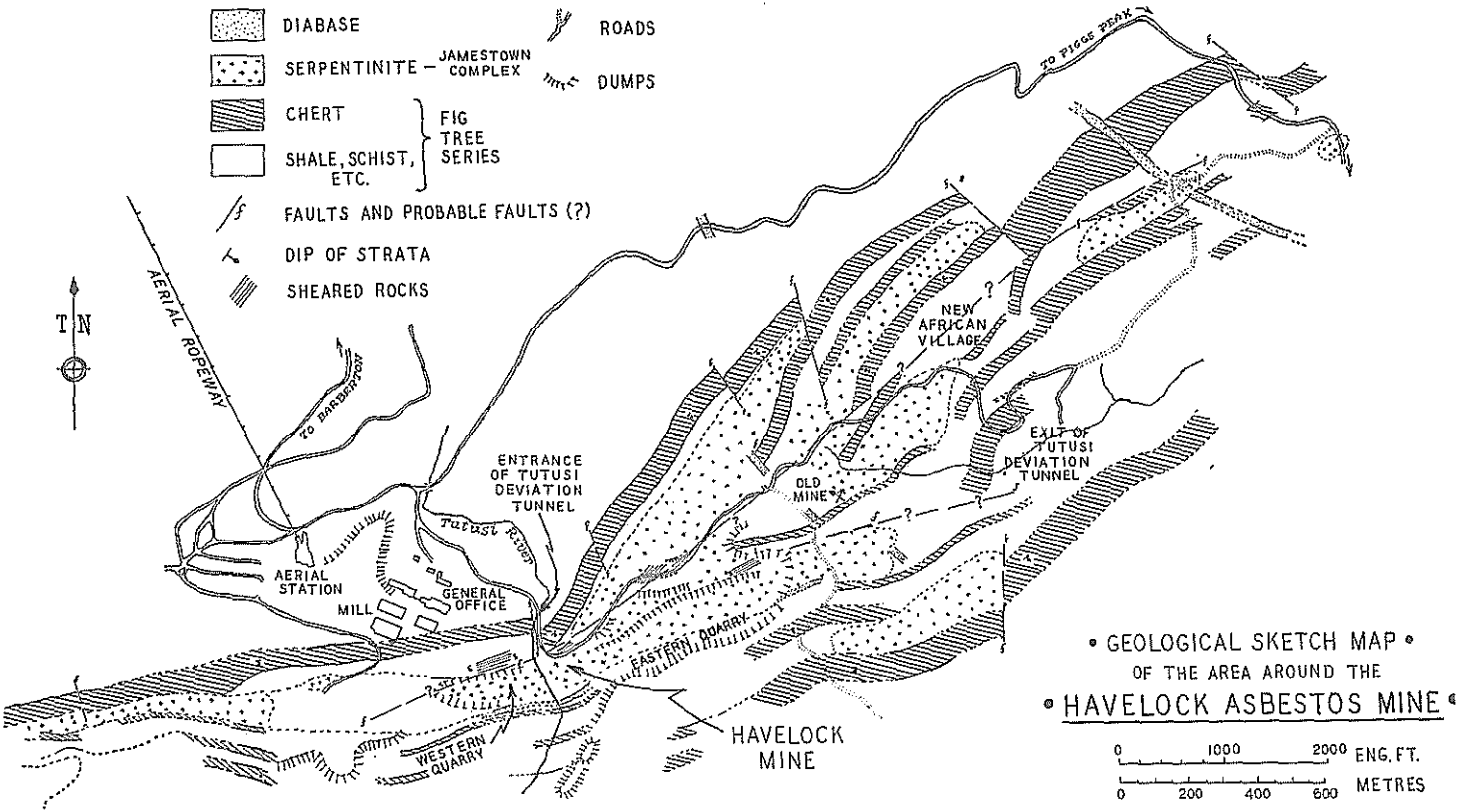
DIABASE
SERPENTINITE — JAMESTOWN COMPLEX
CHERT
SHALE, SCHIST, ETC.
FIG TREE SERIES
ROADS
DUMPS
FAULTS AND PROBABLE FAULTS (?)
DIP OF STRATA
SHEARED ROCKS
T N
AERIAL ROPEWAY
TO BARBERTON
TO PIGGS PEAK
AERIAL STATION
MILL
GENERAL OFFICE
Tutusi River
ENTRANCE OF TUTUSI DEVIATION TUNNEL
NEW AFRICAN VILLAGE
OLD MINE
EXIT OF TUTUSI DEVIATION TUNNEL
EASTERN QUARRY
WESTERN QUARRY
HAVELOCK MINE
• GEOLOGICAL SKETCH MAP •
OF THE AREA AROUND THE
• HAVELOCK ASBESTOS MINE •
0 1000 2000 ENG. FT.
0 200 400 600 METRES

FIG. 1

between 400 and 500 ft. West of the mine the serpentinite is partly obscured under a large mine dump but where it reappears between massive chert it has a width of less than 200 ft. East and north-east of the mine the serpentinite widens considerably up to a maximum width of over 1,400 ft. This widening of the outcrop is almost certainly due to duplication caused by strike faulting. The intense shearing of the serpentinite as seen on surface immediately north of the mine, as well as in the Tutusi Deviation Tunnel, is further evidence that faulting has taken place. Farther to the east, isolated occurrences of serpentinite are found mostly conformable to the enclosing sediments. The true structure of the area has not yet been deciphered but it is quite clear from the sudden disappearance of thick bands of chert that intense faulting has also occurred in this area.

The serpentinite of the Havelock area is composed of both the light green and dark green varieties. Asbestos fibre is restricted, however, to the main orebody and to a small area east of the present mine where it had been exploited in the past. South of the abattoir, intense ferruginization of the country rocks as well as the serpentinite has taken place.

The orebody. The orebody strikes nearly east-west and has a length of about 4,000 ft. with the width varying between 60 and 350 ft., the average being about 110 ft. The dip is southerly and variable (Fig. 2). The orebody 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 orebody is thus determined by an economic pay limit. Since mining seldom penetrates far into the hangingwall, it is difficult to assess the total thickness of the serpentinite. At 17E cross-cut on Third level it is 400 ft. but farther east the thickness decreases and at 30E cross-cut it is less than 200 ft. This decrease in thickness is probably the result of an oblique strike fault which cuts through the orebody and which has not only obscured the true thickness of the serpentinite but also its relationships with the footwall. The intense shearing associated with this fault can be seen on surface and in many cross-cuts into the footwall.

The chrysotile asbestos in the orebody occurs as a stockwork of crossfibre seams forming about 3 to 4 per cent. of the rock and varying in fibre-length from less than $\frac{1}{8}$ in. to, in rare cases, over 2 in. (Plate II (*c*)). Although there is no pronounced orientation of the seams, it would appear as if there is a tendency for the seams to occur in two distinct directions—one dipping at about 70^{0} south and the other at about 15^{0} north.

Mineralogically the host rock of the chrysotile is composed almost entirely of serpentine with isolated remnants of olivine found only at a few localities. Brucite is often present as grains or veinlets. The upper dark green serpentinite into which the orebody grades differs from the lighter green variety in that it contains no brucite but more magnetite. Chemically the lighter green variety is also higher in magnesium and lower in silicon and iron.

The serpentinite is separated from the footwall chert band by a variable thickness of talc-carbonate schist, talc-carbonate-chlorite schist, quartz-carbonate rock and fine-grained amphibolite. The hangingwall of the serpentinite is also formed by fine-grained amphibolite or banded black and white chert followed by alternating talc-carbonate schist, chlorite schist, arenaceous shale and massive chert. In a few places talc-carbonate rock was seen to replace serpentinite as well

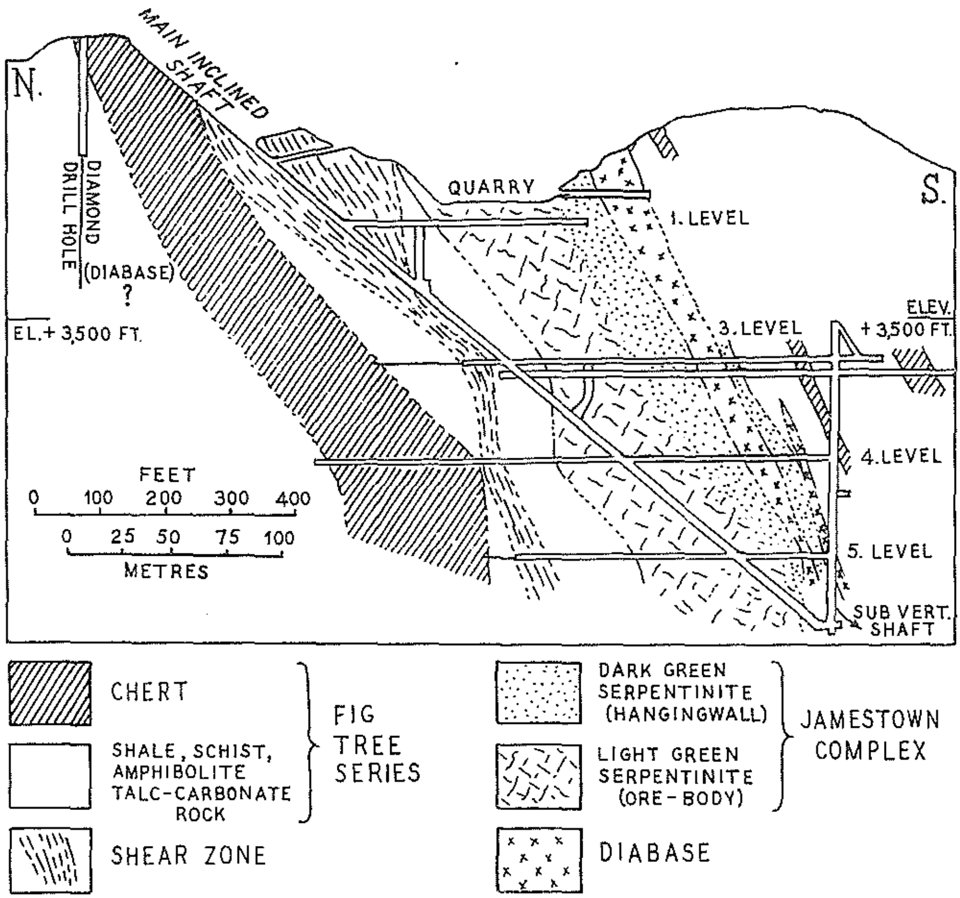

FIG. 2

as chrysotile fibre. The distribution and origin of these replacement bodies have not yet been deciphered.

Intrusive rocks. In the upper portion of the serpentinite, near its contact with overlying sediments, a diabase sill of varying thickness has been emplaced over nearly the entire length of the orebody. The sill, which may be as much as 40 ft. thick, occasionally splits up into two or three thinner sills. Under the microscope it is seen to consist of a fine-grained aggregate of colourless and light green amphibole, probably formed from pyroxene, and highly altered plagioclase with remnants of an ophitic texture clearly visible in places. Several cross-cut dykes, also of variable thickness and shape, and composed of augite, uralite, clinozoisite and uralitized plagioclase, are found in the mine. The relative ages of the various intrusive dykes and sills could not be determined because of a lack of suitable exposures.

The serpentinite is often coloured brown for several feet on either side of the dykes. Fibre occurring in this zone is brittle (due to talcification) but it appears as if some dykes are pre-fibre since seams of asbestos peter out in the vicinity of these dykes.

The nearest exposure of granite to the mine is about six miles away in the Pigg's Peak area.

Faulting. The large strike fault in the footwall of the orebody has already been mentioned. From a displacement of the footwall chert band east of the main inclined shaft, it can be seen that there are also a number of small normal faults. In the serpentinite itself the faults can seldom be traced with certainty because of the lack of marker horizons. "Slip planes," usually filled with magnesite, talc or slipfibre and showing slickensides, indicate that considerable movement has taken place in the orebody. Although it may not be possible to determine the throw on these slips, their orientation and relationship to the large strike fault and to fibre-bearing zones may be of importance.

Mining. The Havelock orebody is mined by a type of sub-level caving. At the time of this investigation mining operations had reached the Fifth level, a depth of about 600 ft. below surface.

The M'Sauli Mine

If the serpentinite, on which the Havelock Mine is situated, is followed westwards it is found to continue down the valley of the M'Sauli River until it is truncated by a large fault (Plate I). About four miles farther south the serpentinite reappears on the eastern side of the fault and it is at this locality that the M'Sauli Mine is situated. The serpentinite in which this orebody occurs is very similar to that of the Havelock Mine, dipping here at about 60° to the east. The fibre is of the same high quality as that of Havelock but a higher percentage of magnetite seemed to be associated with it. At the time of the author's visit, little development had been done. The best fibre appeared to occur in the northern section of the mine towards the large fault running down 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 orebody, but no excavation had been made to expose the argillaceous rocks.

The serpentinite in which 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 as at 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. Farther south near the Oshoek-M'babane 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.

The New Amianthus, Munnik Myburgh and Sunnyside Mines

From just north of Kaapsehoop a belt of rocks, approximately one to two miles wide and belonging to the Fig Tree Series and the Moodies System, intruded by sill-like bodies of serpentinite and diorite belonging to the basic phase of the Jamestown Complex, runs in an east-west direction along the northern boundary of the Kaap Valley Granite (Plate I). 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. 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 three miles due north of the small village of Kaapsehoop, with the Munnik Myburgh Mine approximately three miles to the east of the village. The Sunnyside Asbestos Mine is situated about three 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 fold (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 formerly correlated with the Ventersdorp System by Hall (1930, p. 110), but now considered to be the equivalent of the Dominion Reef System (Truter, 1949). 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 westward 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 ft. 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 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. 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. 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 ft. wide and nearly 200 ft. long.

The fault which cuts across the serpentinites at the Sunnyside Mine is probably the same as that against which the fibre horizons terminate at the Munnik Myburgh. The main horizon worked at this mine would then be the equivalent of the "Griffin" line.

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 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 eighth level, the serpentinite terminates against basic schist. 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; it often peters out in patches of brown (chocolate) serpentinite and usually consists of a few seams of long fibre associated with a great number of very thin parallel seams.

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 reopened 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 7 ft. the upper 3 ft. contained 15 seams per linear foot with fibre length varying between ½ and ¼ in. The lower 4 ft. contained 30 seams per linear foot with fibre lengths between ¼ and $\frac{1}{16}$ in. Over 7 ft. the rock contained about 40 per cent. 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 in. were not uncommon, and in one case fibre of up to 8 in. 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.

The Sterkspruit Mine

In the Komati valley on the farms Sterkspruit 239, Stolzburg 202 and Doyershoek 145 are sill-like bodies of light green serpentinite alternating with layers of dark blue-green serpentinite. 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 in.) 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 ft., fibre of good quality and measuring from ½ to ¾ in. 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 the farm 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 9,000 ft. but has been produced economically only from a few isolated places. The pyroxenite forming the top of the ridge is only between 40 and 50 ft. wide, but occurs along the whole length of the property. The dip of the pyroxenite, 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 pyroxenite 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 outcrops. In the vicinity of these displacements the serpentinite is intensely sheared.

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

In thin sections of the pyroxenite 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 ($2V_z = 54°$, $Z > c = 44°$) even though the birefringence is on the low side (First Order yellow and red interference colours).

At the Hill Top Quarry, situated at the eastern extremity of the deposit, chrysotile asbestos occurs in an unusual and interesting manner (Plate II, e). 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. In the light green serpentinite seams of chrysotile asbestos, with average fibre lengths of between ⅛ in. and ¼ in., but occasionally as long as ½ in. or even ¾ in., 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 show entirely different textures (Plate III, a and b). The dark green core consists of vein-type serpentine, often in the form of oval grains lying in a matrix of structureless serpentine. This pattern is reminiscent of that of olivine grains included in pyroxene, even to the extent of showing radiating expansion fractures. 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 cross-hatched texture. Apart from the larger chrysotile veins, no vein-type serpentine could be seen under the microscope. This indicates 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 almost 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. 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, it was formed 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 100 ft. Diabase of great thickness was also intersected in some of the diamond drill holes. Borehole W.4 went through diabase for the first 150 ft. while borehole Y.3 intersected nearly 100 ft. 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 per cent. anorthite. In a few specimens chlorite, talc and quartz in intergrowth with feldspar 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 underground 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. This diabase varies considerably in texture. It may be fine-grained and even-grained or consist of long needles of hornblende in a matrix of altered plagioclase. Clinozoisite is found as small crystals in the feldspar.

At several places underground in the central section, as well as in the immediate hangingwall of the orebody in the Hill Top Quarry, leucocratic dykes (called feldspar by the miners), up to 10 ft. 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, clinozoisite 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 ends abruptly when followed westwards. Intense shearing of the serpentinite can be seen at this point as well as farther 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.

Barberton Chrysotile Mine

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

The chrysotile asbestos here occurs in serpentinite belonging to the basic phase of the Jamestown Complex. The serpentinite takes the form of sill-like bodies surrounded by amphibole schist which 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.

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 orebody, which varies in width from 35 to over 100 ft., dips at angles from 30° to 40° 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 $\frac{1}{2}$ in., is in the form of a stockwork. "Ribbon"-type fibre is also found and is usually considered by the miners to indicate the proximity of either the hangingwall 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.

Kalkkloof Asbestos Mine

On the farm Kalkkloof 250, which lies in a straight line about six 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. 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; farther 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 and 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 NNE and dip at about 60° WNW. 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 recognized from the bottom upwards: the Millsite Lode, the X-Lode, the Main Lode, the New Lode and, right at the top, the Amianthus Lode. Of these, the X-Lode and the Main Lode are the most important fibre-bearing zones. An inclined shaft, dipping at about 30°, has been put down in the light green serpentinite between the two lodes and cross-cuts have been driven approximately every 200ft. along the incline. The horizontal distance between the two lodes varies from 200 to 250 ft.

The Main Lode is about 5 ft. 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 1 in. This arrangement reminds one strongly of the Ribbon Line of the Amianthus Mine and 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-Lode and the Main Lode on Third level. In most cases a thin rim of magnetite surrounds the barbertonite and in some magnetite also occurs in the centre of the grain. Veinlets of barbertonite also exist.

On First level the serpentinite between the X-Lode and the Main Lode has been replaced nearly completely by carbonate. Remnants of serpentinite, with small amounts of talc and magnetite skeleton crystals, occur in a fine-grained calcareous matrix.

The dark green serpentinite between the Main and New Lodes on Third 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 cross-cutting diabase dykes are found in the underground workings. One of these is exposed on surface between the X-Lode and the Main Lode. 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. 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.

Occurrences of Chrysotile Asbestos in the Serpentinized Dolomite of the Transvaal System

General

The Dolomite Series of the Transvaal System in the Eastern Transvaal decreases in thickness from nearly 2,000 ft. near Pilgrim's Rest to just over 100 ft. at Carolina. It is composed mainly of massive dark gray 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 in the succession they become massive and may be as thick as 30 ft. (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 interbedded in the dolomite.

Along several horizons in the dolomite, sheets of diabase, and in places pyroxenite or peridotite, probably of Bushveld age, have been intruded. They vary in thickness from a few feet to over 150 ft. 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 gray 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 ft. 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 farther 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). As far as the author could determine, fibre occurred associated with both diabase sills and sills of ultrabasic composition. The composition of the sill did not seem to determine whether fibre would develop.

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.

Congo-Vaal Asbestos Mine

This mine is situated on the farm Rietfontein 70 which lies about 22 miles due east of Carolina. The fibre occurs in the serpentinized dolomite 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 100 ft. 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. Along the southern contact of the dyke a peculiar reddish-gray 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 in. 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 is more than 400 ft. 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 analyzed chemically 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 in. 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.

The Carolina Asbestos Mine on the Farm Diepgezet 33 *and the Deposit on Zilverkop* 31

The occurrence of chrysotile on both the farms Diepgezet 33 and 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 also 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 the succession—15 to 20 ft. below the Rooihoogte quartzite and shales of the Pretoria Series. The Zilverkop occurrence lies on the same horizon about one 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, 14 tons of hand-cobbed fibre were produced of which nearly 50 per cent. was over 1 in. 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.

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 one of the mine workings penetrated the diabase dyke.

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 five miles due west of the confluence of the Elânds 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 ft. Higher along the slope and towards the crest of an east-west spur the dyke decreases in width to a mere 30 ft. (T. W. Gevers—unpublished report). Near the main workings a second dyke about 20 ft. wide was noticed parallel to the main dyke. The two dykes are separated by about 30 ft. 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 orthopyroxene largely altered to serpentine.

Most of the fibre is less than ½ in. in length, although some seams of over ¾ in. 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 in. of fibre over a width of 18 in. 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 ft. The fibre zone, however, appeared to pinch out downwards.

Other Occurrences

Apart from the abovementioned 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 (Hall, 1930, p. 222). The dolomite at the mine forms a krantz approximately 35 ft. high and is then followed by the "Blyde River 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 1½ in. in length. It has been mined out up to the dyke, but because of faulting further development went through the dyke into the footwall 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 ft. west of the dyke and only very short fibre (less than ¼ in. in length) was noticed in the serpentinized dolomite.

Olifantsgeraamte 459. This occurrence is situated some four to five miles west of Sabie on the property of the South African Forest Investments Limited. The fibre 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 downthrow of about 40 ft. on the eastern side. 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. The displacement is only about 6 ft. 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 in. in length 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 ft.

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 with faulting or with fault-dykes. It was then decided to visit the abovementioned farms and to inspect the areas where the fibre could possibly exist.

On Uitkomst, just north of the point where the fault-dyke cuts through the Gladde Spruit, several adits were found exposing chrysotile asbestos up to $\frac{3}{4}$ in. 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 in. 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 slope of a broad valley with the result that exposures are very poor. Brittle fibre, 1 in. in length, was 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 $\frac{3}{4}$ in. in length and of good quality was found above a diabase sill near this dyke.

THE MINERALOGY OF THE SERPENTINE MINERALS

Before discussing the origin of serpentinite and chrysotile asbestos it would be well to give a brief outline of the present knowledge of the mineralogy of the serpentine minerals. A comprehensive summary of all the early work is given by Selfridge (1936). From his work, which was based on both X-ray and optical studies, he concludes that only two serpentine minerals exist, namely, serpentine and antigorite. Chrysotile is the fibrous form of serpentine and the name serpentinite is suggested for a rock containing both minerals. Gruner (1937) agrees with Warren and Bragg (1930) that chrysotile has a double-chain structure like that of the amphiboles. Antigorite may have a chain-like or a sheet-like structure. According to him also only two serpentine minerals exist—chrysotile and antigorite—and when it is not possible to distinguish between them the name serpentine should be used. The uncertainty over the structure of the serpentine minerals was partly the result of the poor X-ray patterns (broad lines) obtained from chrysotile, and partly because Pauling (1930) had predicted that there would not be a magnesium analogue of the kaolinite structure because of the difference in sizes of the octahedral and tetrahedral layers. He also suggested that if serpentine did have the kaolinite structure the sheets would tend to curve. Warren and Hering (1941) examined the structure of chrysotile asbestos and came to the conclusion that it did have a kaolinite layered structure. This view was further supported by the work of Aruja (1945). In 1950, Bates and Mink established by means of electron microscope studies that chrysotile asbestos consisted of minute tubes. They suggested that the relationship between antigorite (with a platy habit) and chrysotile (with a tubular habit) was similar to that between kaolinite and halloysite (see Plate III, *d*, *e* and *f*).

Since then the structure of the serpentine minerals has been investigated in great detail by Noll and Kircher (1951), Nagy and Bates (1952), Zussman (1954), Brindley and Von Knorring (1954), Jagodzinski and Kunze (1954), Whittaker and Zussman (1956), Nagy and Faust (1956), Kalousek and Muttart (1957) and many others. From X-ray studies Whittaker and Zussman (1956) recognized a third serpentine mineral to which they gave the name lizardite. The following classification of the serpentine minerals was suggested by them:

serpentine $Mg_6Si_4O_{10}(OH)_8$	chrysotile (fibrous)	clino-chrysotile ortho-chrysotile para-chrysotile
	lizardite (platy)	
	antigorite (platy)	

They also found that serpentinites from different localities contained varying proportions of these minerals but the reasons why any particular type occurred could not be established. Nagy and Faust (1956) further suggested that since the magnesium in the serpentine minerals could be replaced by iron, nickel and manganese a further subdivision into ferro-, nickel- and manganese-chrysotile and antigorite could be effected. The latter would, however, only exist as hypothetical end members and in nature isomorphous mixtures between these and magnesium-serpentine would occur. The authors also determined that the chrysotile structure was less stable than that of antigorite with respect to attack by acid and disintegration in the electron beam. This confirmed the work of Sobolev (1945), Hess, Smith and Dengo (1952) and Nagy (1953) who had found chrysotile recrystallizing into antigorite. To the present author it is not altogether clear why this should be so. If the layered structure of the serpentine minerals is unstable because of a misfit between the layers (as suggested by Pauling, 1930) then one would expect chrysotile, with a tubular structure, to be more stable than the platy antigorite since the misfit will have been compensated for by the curvature of the tubes. However, it may be that the platy habit of antigorite is stabilized through the presence of additional Al or Fe ions replacing Mg in the structure. It was in fact found by Nagy and Faust (1956) that chrysotiles contained 1·9 per cent. to 2·9 per cent. Al_2O_3 or Fe_2O_3 while antigorites contained 2·9 per cent. to 6·5 per cent. Al_2O_3 or Fe_2O_3. This was confirmed by the author in specimens from the present area where non-fibrous serpentines all had a higher Al_2O_3 or Fe_2O_3 content than the chrysotiles investigated (W. J. van Biljon, 1959, p. 70 and 1960, p. 1227). Deer, Howie and Zussman (1962, p. 178), however, point out that this is not always the case and that some antigorites have Al_2O_3 and Fe_2O_3 contents less than some chrysotiles. The present author feels that care should be taken in arriving at conclusions because the presence of a small amount of impurities existing as coatings on fibres may give erroneous results (Plate II*d*). Calculations by the author from chemical analyses and assuming a formula $Mg_6Si_4O_{10}(OH)_8$ for serpentine indicated that impurities in the form of magnetite, hematite, spinel, calcite, dolomite, brucite, talc and possibly opal were present in many of the specimens examined (W. J. van Biljon, 1959, p. 72).

A further difficulty arises if it is assumed that certain antigorites have an undulating structure which naturally will have the same compensating effect on the misfit as the tubular structure of chrysotile.

In spite of the uncertainty which still exists over the stability regions of the various serpentine minerals the present author feels that the relationship between a platy structure in antigorite and a tubular (elongate) structure in chrysotile is of great importance in the formation of asbestos deposits.

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.

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.

Serpentinized Dolomite

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 4 to 5 ft. of de-dolomitized limestone. A particular zone of serpentinite may end abruptly with another starting on a different horizon, either nearer to or farther 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.

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 10 ft. wide on both sides of the dyke.

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 of 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 conductivity 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 thermodiffusion will concentrate magnesium near the intrusion and calcium farther 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 farther 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 dependent 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°—1,000°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. Farther 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:

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

below 500°C:

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

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 elsewhere 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 are composed of diabase but on Elandshoek the dyke grades into pyroxenite. The difference in composition did not seem to influence the amount of serpentinization occurring along the dyke (T. W. Gevers, unpublished report).

Massive Serpentinite

Nature. The massive serpentinites, such as 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 ultrabasics (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 clinozoisite, 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 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 fourth level, while the serpentinite on fifth level (150 ft. 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, both Hall (1930) and 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 (Plate I).

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.

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 peridotite 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 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 1,000°C even if the vapour pressure is as high as 15,000 p.s.i. If one accepts the laboratory evidence the theories of Hess must be considered to be untenable, in spite of Bowen's objections, evidence from the Thetford area, Canada, pointing 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 this 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 led 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 autometasomatism 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 autometasomatic. 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:

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

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 a 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 deep-seated 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 1,000 ft., 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 2,000 ft. 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. From a chemical investigation carried out by the author 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.

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 suggestive of a genetic relationship between the granites and the ultrabasic rocks.

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 resister" 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 aforegoing 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 ultrabasic 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's "basic front" theory may offer a solution.

(*c*) The relationship between certain sediments and the serpentinites also possesses 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 the author was mainly interested in the origin of chrysotile asbestos, and not in the origin of serpentinite, this problem has not been 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.

Chrysotile Asbestos

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 in., 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. 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 farther 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. 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.

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 feet to as many as 30 seams per linear foot over several feet (Hall, 1930, 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. Single seams may also split or branch to join other seams but only in a few cases was one seam seen to cut another. 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. This orientation is, however, of a regional nature and a particular set of veins may exist only for a small distance. Farther 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 2½ in. on Fourth 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." 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.

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. Occasionally magnetite as well as magnesite occurs at the junction of seams. Only rarely was a seam seen to cross 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. 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. 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. 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. This dense serpentine is isotropic under the microscope and resembles material formed from colloidal suspension. Similar material from the Havelock Mine consists of short needles, as shown by the electron microscope. Along strike this material grades into chrysotile.

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 of silica and a decrease in the amounts of magnesia and water. An extremely small amount of talc admixed with fibre may make the fibre soft to the touch 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 content of magnesia and water and a lower content of silica and iron 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 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 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 due to talcification in most cases. Spoilt fibre from Havelock Mine 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 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. 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, cross-fibre veins consisting mainly of magnetite with intersitial 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.

The Origin of Chrysotile Asbestos

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 expect in such a case 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 is that the fibre grew at the expense of the wall rocks, that is, replacing the serpentinite during 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 (Plate III (*c*)). 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.

The third possible mode of formation is that the fibre grew in fractures either by pushing the walls apart (Taber, 1916a, 1916b, 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; 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 considered, 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 later in this paper.

The stability of antigorite and chrysotile. 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 higher percentages of 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.

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. 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.

The chemical analysis of dense apple-green serpentinite shows relatively high percentages 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. 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.

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 being 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 occurring 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 orebody; 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 could 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 seem to the author that here, too, tension has played an important rule in the formation of the fibre.

In the case of the "boulder formation" occurring at the Stolzburg Mine, it has been stated that the boulders lie at the centres of blocks outlined by a system of joints next to a pyroxenite dyke. From chemical investigations 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 have lead to a system of more or less radial fractures with fibre formation.

From this 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.

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 solution). 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 2,000 ft. Normally meteoric water is restricted to a depth of approximately 1,000 ft. 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 water 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, such as magnesium, iron or silicon, will be deposited as brucite, magnetite or opal along partings or along the edges of veins.

The upper stability temperature for serpentine has been established as 500°C or 450°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°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. The author is of the opinion that detailed measurements on chrysotile vein orientation as well as measurements of the direction of fibres in the veins may indicate the structural pattern which governed the growth of the fibre. This could be of major economic significance.

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REFERENCES

ARUJA, E. (1945). An X-ray study of the crystal-structure of antigorite. *Min. Mag.*, Vol. 27, pp. 65–74.

AVIAS, J. (1955). Relations Minéralogiques et Geóchemiques entre les Serpentines et Peridotites de Nouvelle Calédonie, leur inclusions, leur enclaves, les roches encaissantes. *Coll. Int. Nat. Recher. Sci.*, LXVIII.

BAIN, G. W. (1932). Chrysotile asbestos II. Chrysotile solutions. *Econ. Geol.*, Vol. 27, pp. 281–296.

BALDUZZI, F., EPRECHT, W. and NIGGLI, P. (1951). Weitere Versuche zur Synthese von Chrysotilasbest. *Schweizer. min. pet. Mitt.*, Vol. 31, pp. 293–305.

BARTH, T. F. W. (1952). *Theoretical Petrology.* New York: John Wiley and Sons.

BATES, T. F. and MINK, J. F. (1950. Morphology of the serpentine minerals, *Tech. Rep.*, No. III. Contract No. N6 onr 26914 Pennsylvania State College (Abstract in: *Bull. geol. Soc. Amer.*, Vol. 61).

—— SAND, L. B. and MINK, J. F. (1950). Tubular crystals of chrysotile asbestos. *Science* Vol. III.

BENSON, W. N. (1918). The origin of serpentine. *Amer. Jour. Sci.*, Vol. 46.

—— (1926). The tectonic conditions accompanying the intrusion of basic and ultrabasic plutonic rocks. *Nat. Acad. Sci.* (Washington), Vol. 19, Mem. I.

BOWEN, N. L. (1928). *Evolution of the Igneous Rocks.* Princeton University Press.

—— and TUTTLE, O. F. (1949). The system $MgO–SiO_2–H_2O$. *Bull. geol. Soc. Amer.*, Vol. 60, pp. 439–460.

BOYDELL, H. C. (1926). A discussion of metasomatism and the force of growing crystals. *Econ. Geol.*, Vol. 21, pp. 1–55.

BRINDLEY, G. W. (1954). The structural formula of an antigorite from Venezuela. *Amer. Min.*, Vol. 39, pp. 391–394.

—— and VON KNORRING, O. (1954). A new variety of antigorite (ortho-antigorite) from Unst, Shetland Islands. *Amer. Min.*, Vol. 39, pp. 794–804.

COOKE, H. C. (1937). Thetford, Disraeli and eastern half of Warwick Map Areas, Quebec. *Mem. geol. Surv. Canada*, 211, pp. 86–140.

DEER, W. A., HOWIE, R. A. and ZUSSMAN, J. (1962). *Rock-forming Minerals*, Vol. 3. Sheet silicates. London: Longmans.

DALY, R. A. (1933). *Igneous Rocks and the Depths of the Earth.* New York: McGraw Hill.

DE SITTER, L. U. (1956). *Structural Geology.* New York: McGraw Hill.

DRESSER, J. A. (1913). Preliminary report on the serpentine and associated rocks of southern Quebec. *Mem. geol. Surv. Canada*, 22, pp. 61–67.

EPPRECHT, W. (1947). Versuche zur Synthese von Serpentin-Mineralien. *Schweizer. min. pet. Mitt.*, Vol. 27, pp. 1–20.

GRUNER, J. W. (1937). Notes on the structures of serpentines. *Amer. Min.*, Vol. 22, pp. 97–103.

—— (1948). Progress in silicate structures. *Amer. Min.*, Vol. 33, pp. 679–691.

GRAHAM, R. P. D. (1917). Origin of massive serpentine and chrysotile asbestos. Black Lake, Thetford area, Quebec. *Econ. Geol.*, Vol. 12, pp. 154–202.

—— (1944). Serpentine belt, Eastern Townships, in geology of Quebec. *Rep. Quebec Dept. Mines Geol.*, 20, II, pp. 439–443.

HALL, A. L. (1913). The geology of the country N.E. of Carolina. *Annu. Rep. geol. Surv. S. Afr.*, pp. 31–60.

—— (1930). Asbestos in the Union of South Africa. *Mem. geol. Surv. S. Afr.*, 12.

HESS, H. H. (1933). The problem of serpentinization and the origin of certain chrysotile, talc and soapstone deposits. *Econ. Geol.*, Vol. 28, pp. 634–657.

—— (1938). A primary peridotite magma. *Amer. J. Sci.*, Vol. 35, pp. 321–344.

—— SMITH, R. J. and DENGO, G. (1952). Antigorite from the vicinity of Caracas, Venezuela. *Amer. Min.*, Vol. 17, pp. 68–75.

JAGODZINSKI, H. and KUNZE, G. (1954). Die Rölchenstruktur des Chrysotils, I, II und III. *Neues Jb. Min. Monatsch.* 4, 5, 6 und 7.

JANDER, W. and FETT, R. (1939). Hydrothermale Reaktionen II Magnesium Silikate. *Zeits. anorg. allg. Chemie*, Vol. 242, pp. 145–160.

—— and WUHRER, J. (1938). Hydrothermale Reaktionen I. Die Bildung von Magnesiumhydrosilikaten. *Zeits. anorg. allg. Chemie*, Vol. 235, pp. 273–294.

KALOUSEK, G. L. and MUTTART, L. E. (1957). Studies on the chrysotile and antigorite components of serpentine. *Amer. Min.*, Vol. 42, p. 1.

KEEP, F. E. (1929). The geology of the Shabani Mineral Belt, Belingwe district. *Bull. geol. Surv. S. Rhodesia*, 12.

KEITH, I. S. B. and BAIN, G. W. (1932). Chrysotile Asbestos I. Chrysotile veins. *Econ. Geol.*, Vol. 27, pp. 169–188.

—— and TUTTLE, O. F. (1952). Significance of variation in the high-low inversion of quartz. *Amer. J. Sci.*, Bowen Vol., pp. 203–280.

NAGY, B. (1953). The textural pattern of the serpentines. *Econ. Geol.*, Vol. 48, pp. 591–597.

—— and BATES, T. F. (1952). Stability of chrysotile asbestos. *Amer. Min.*, Vol. 37, pp. 1055–1058.

—— and FAUST, G. T. (1956). Serpentine: a natural mixture of chrysotile and antigorite. *Amer. Min.*, Vol. 41, pp. 817–837.

NEWHOUSE, W. H. (1942). *Ore deposits as related to structural features.* Princeton University Press.

NOLL, W. and KIRCHER, H. (1951). Über die Morphologie von Asbesten und ihren Zusammenhang mit der Kristaalstruktur. *Neues Jb. Min. Monatsh.* 10, pp. 219–240.

PAULING, L. (1930). The structure of the chlorites. *Proc. Nat. Acad. Sci.*, Vol. 16, pp. 578–582.

POLDERVAART, A. (1950). Chrysotile asbestos produced by dolerite intrusions in dolomite. *Colonial Geol. Min. Resour.*, Vol. 1, pp. 239–245.

PROUD, J. S. and OSBORNE, G. D. (1952). Stress environment in the development of chrysotile. *Econ. Geol.*, Vol. 47, pp. 13–23.

RAMBERG, H. (1952). *The origin of the metamorphic and the metasomatic rocks.* University of Chicago Press.

READ, H. H. (1951). Metamorphism and granitization. Alex L. du Toit Mem. Lecture (2). *Trans. geol. Soc. S. Afr.*, Annex Vol. 54.

REYNOLDS, D. (1947). Basic "fronts" and granitization. *Sci. Progr.*, Vol. 35.

RIORDON, P. H. (1955). The genesis of asbestos in ultrabasic rocks. *Econ. Geol.* Vol. 50, pp. 67–81.

SELFRIDGE, G. C. (1936). An X-ray and optical examination of the serpentine minerals. *Amer. Min.*, Vol. 21, pp. 463–501.

SOBOLEFF, N. D. (1945). Microtexture of serpentinites. *Akad. Nauk. U.S.S.R. Doklady*, Vol. 50, pp. 455–456. *Chem. Abs* (1950), Vol. 44, p. 5282 f.

—— and TARANINOFF, M. V. (1933). Cause of brittleness in chrysotile asbestos. *Econ. Geol.*, Vol. 28, pp. 171–177.

TABER, S. (1916a). The genesis of asbestos and asbestiform minerals. *Bull. Amer. Min. Eng.*, pp. 1973–1998.

—— (1916 *b*). On the growth of crystals under external pressure. *Amer. J. Sci.*, Vol. 41, pp. 532–556.

—— (1917). The origin of chrysotile veins. *Econ. Geol.*, Vol. 12, pp. 476–479.

—— (1924). The origin of veins of fibrous minerals. *Econ. Geol.*, Vol. 19, pp. 475–486.

—— (1926). Metasomatism and the pressure of growing crystals. *Econ. Geol.*, Vol. 21, pp. 717–727.

TRUTER, F. C. (1949). A review of volcanism in the geological history of South Africa. *Trans. geol. Soc. S. Afr.*, Vol. 52, pp. xxix–lxxxviii.

TURKEVICH, J. and HILLIER, J. (1949). Electron microscopy of colloidal systems. *Anal. Chem.*, Vol. 21, pp. 475–485.

TURNER, F. J. and VERHOOGEN, J. (1951). *Igneous and Metamorphic Petrology*. New York: McGraw Hill.

UMBGROVE, J. H. F. (1947). *The Pulse of the Earth*. Den Haag: Martinus Nijhoff.

URIE, J. G. (1958). *The Geology of the Bomvu Ridge Iron Deposits*. M.Sc. Thesis, University of the Witwatersrand.

VAN BILJON, S. (1949). The transformation of the upper part of the Pretoria Series in the Bushveld Igneous Complex. *Trans. geol. Soc. S. Afr.*, Vol. 52, pp. 1–175.

VAN BILJON, W. J. (1959). *The Nature and Origin of the Chrysotile Asbestos Deposits of Swaziland and the Eastern Transvaal*. Ph.D. thesis, University of the Witwatersrand.

—— (1960). Chemical reactions in the thermal breakdown of the serpentine minerals. *N. Jb. Min., Abh.*, Vol. 94, Festband Ramdohr, pp. 1223–1240.

VAN EEDEN, O. R. (1941). *Die Geologie van die Sheba Rante*. M.Sc. Thesis, University of Pretoria.

—— *et al.* (1956). The geology of the Barberton area. *Geol. Surv. Union S. Afr.* Special publ. 15.

VISSER, D. J. L. (1957). The structural evolution of the Union. *Trans. geol. Soc. S. Afr.* Vol. 60, pp. xiii–xlix.

WARREN, B. E. and BRAGG, W. L. (1930). The structure of chrysotile $H_4Mg_3Si_2O_9$. *Zeit. Krist.*, Vol. 76, pp. 201–210.

—— and HERING, K. W. (1941). The random structure of chrysotile asbestos. *Phys. Rev.*, Vol. 59, p. 925.

WHITTAKER, E. J. W. and ZUSSMAN, J. (1956). The characterization of the serpentine minerals by X-ray diffraction. *Min. Mag.*, Vol. 31, pp. 107–126.

WILLEMSE, J. (1937). On the old-granite of the Vredefort region and some of its associated rocks. *Trans. geol. Soc. S. Afr.*, Vol. 40, pp. 43–120.

WORST, B. G. (1958). The differentiation and structure of the Great Dyke of Southern Rhodesia. *Trans. geol. Soc. S. Afr.*, Vol. 61.

YODER, H. S. (Jnr.) (1952). The $MgO–Al_2O_3–SiO_2–H_2O$ system and the related metamorphic facies. *Amer. J. Sci.*, Bowen Vol., part II, pp. 569–623.

ZUSSMAN, J. (1954). An investigation of the crystal structure of antigorite. *Min. Mag.*, Vol. 30, pp. 498–512.

—— (1956). Antigorite: super lattice and structural formula. *Amer. Min.*, Vol. 41, pp. 148–152.