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THE HAVELOCK ASBESTOS DEPOSIT IN SWAZILAND, BARBERTON GREENSTONE BELT*

by

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ABSTRACT

The Havelock asbestos deposit is one of the most important occurrences of cross-fibre chrysotile in southern Africa. The asbestos ore body occurs within a serpentinized dunite–harzburgite that contains the primary serpentinite assemblage lizardite–chrysotile–brucite–magnetite. While the transition from dunite to harzburgite is a progressive change in composition, consistent with fractional crystallization in a layered intrusion, the ultramafic complex does not itself occupy a stratigraphic horizon. Structural relations and the absence of gabbroic or similar differentiates suggest, instead, that the serpentinite was emplaced along fractures as a solid body. Though the serpentinite is allochthonous, it may be derived from the crustal ultramafic successions of the Barberton greenstone belt. However, the rather depleted compositions of undeformed Havelock serpentinites are also comparable with metamorphic peridotites from younger orogenic belts and serpentinites dredged from the present sea floor. An alternative hypothesis, that the Havelock body is an Alpine-type serpentinite, cannot be excluded from the present evidence.

Although the margins of the Havelock body are tectonic, large plastic strains are only recorded in the centre of the serpentinite. A deformed zone of ribbon-textured serpentinites parallels one margin of the asbestos deposit and indicates that internal deformation of the serpentinite and formation of the chrysotile ore body were synchronous. Fibrous chrysotile within the ore body probably formed by diffusion of fluids into dilating cracks at temperatures below dehydration of lizardite serpentinites. Massive circulation of fluids is suggested from the presence of talc zones with fault-like geometry, and the extent of ore body hydration and carbonation. A model is described in which processes of rock dilatancy, diffusion and fluid circulation operated in that part of the serpentinite where tectonic stress rose to relatively high levels.

CONTENTS

I. INTRODUCTION

Metamorphic peridotites, including some that contain deposits of chrysotile asbestos, are found in many young orogenic belts and are widely thought to represent fragments of depleted upper mantle (see Coleman, 1977 for a review). By comparison many greenstone belts (and particularly the Barberton greenstone belt) contain intrusive and volcanic sequences considered to have crystallized directly from magmas of ultramafic composition (Viljoen and Viljoen, 1969a). It appears that lithologies with peridotitic compositions can occur in Archaean crustal sequences without requiring extensive fractional crystallization or large deformations. Since greenstone belt terranes often are highly deformed, the field identification of an Alpine-type serpentinite within such sequences is not likely to be straightforward.

The Havelock ultramafic complex is one of a number of steeply inclined serpentinite bodies that crop out along the south-eastern edge of the Barberton greenstone belt (Fig. 1). Deformation and chemical and mineralogical alteration are characteristic of this ancient tectonic regime. In Swaziland, serpentinites are often found close to large thrust faults and are extensively replaced by talc. The Havelock body is one of the better preserved serpentinites, and the only one in Swaziland known to contain economic vein chrysotile (Urie, 1961).

*This paper has appeared in a similar form elsewhere as part of a full description of the mineral resources of the Barberton greenstone belt in north-west Swaziland (Barton, 1982).

It has been suggested that the chrysotile-bearing ultramafic complexes in the Barberton area represent differentiated sill-like intrusions (Viljoen and Viljoen, 1969b, c; Anhaeusser, 1976). Therefore, particular attention has been given to documenting the field relations, internal composition, and nature of the margins of the Havelock body. Although there is evidence that fractional crystallization operated within the Havelock body (and differentiation of a sill cannot be excluded), it is emphasized here that the serpentinite is allochthonous. It is argued below that the serpentinite reached its present position primarily by tectonic processes.

Economic asbestos occurs within the Havelock serpentinite as a stockwork of chrysotile seams. From the evidence available, it seems likely that the ore body formed principally as a result of deformation accompanied by the motion of fluids. For this reason, the distribution of deformation textures, and a comparison with equivalent experimentally deformed serpentinites are discussed briefly. Because of the relatively large proportion of hydrated ultramafic material in the Barberton area, these data may also be applicable to bulk physical properties such as the crustal strength of the greenstone belt.

II. MINE HISTORY AND PRODUCTION

The Havelock mining lease area falls within the now lapsed Mineral Concession 41, originally granted to Thomas Rathbone on behalf of a prospecting syndicate. In 1886, the area ceded to Rathbone was named the Havelock Concession, after the then Governor of Natal, Sir Arthur Havelock.

Although gold and asbestos were discovered on the Concession in 1887, asbestos did not receive serious attention until 1918 when Izaak Holtzhausen of Barberton rediscovered the Havelock deposit. The present owners began underground exploration in 1929, and exercised their option to purchase the property in 1930. Opening of the mine was delayed until 1939 when the first fibre was processed by the mill. An aerial ropeway was completed during the same year, and connects the mine with the nearest railhead at Barberton. The ropeway is 20 km long and transports the asbestos over the rugged terrain of the Barberton Mountain Land.

Early quarrying operations at Havelock gradually declined and by 1948 the operation became almost totally sub-surface. At first, the mine was served by a three-compartment incline shaft comprising two hoisting compartments and one travelling way. Since 1964, access to the mine has been via a single 6,1 m diameter vertical shaft. The principal mining method is a type of caving (sub-level shrinkage), in which sub-levels are established at 12 m intervals and main haulage levels 72 m apart.

Total recorded production of chrysotile asbestos (1939–1980) is 1,25 Mt, an average of 30 000 t per annum. The contribution of asbestos sales to the economy of Swaziland has been substantial. During the early years of production, asbestos was the most valuable export commodity in the Kingdom, surpassing sugar and wood pulp. Sales of asbestos are still an important earner of foreign currency, and in 1980 accounted for 85 per cent of the total ex-mine revenue in Swaziland.

III. REGIONAL GEOLOGY

Though there are few written accounts of the geology on the Swaziland side of the Barberton greenstone belt, the distribution of massive serpentinites in Fig. 1 is known from detailed mapping by the Swaziland Geological Survey (Hunter and Jones, 1968, 1969; Urie, 1970, 1971). This work has shown that the Havelock body occurs in ground mapped as part of the Onverwacht Group. The Onverwacht Group forms the basal sequence of the Barberton greenstone belt, and together with the overlying Fig Tree and Moodies groups constitutes the Barberton Sequence of the Swaziland Supergroup.

According to the stratigraphy of Viljoen and Viljoen (1969b), the Havelock serpentinite occurs as a conformable lense within the uppermost division of the Onverwacht Group (Zwartkoppie Formation of the Geluk Subgroup). These authors maintained that serpentinite pods of the type shown in Fig. 1 occupy stratigraphic horizons within the Onverwacht Group. They considered that both the Havelock body and the closely related Msauli serpentinite in KaNgwane (formerly part of the Eastern Transvaal) originally formed a continuous or near-continuous differentiated sill (Fig. 1). Viljoen and Viljoen (1969b) believed that deformation has disrupted the sill and produced isolated serpentinite boudins.

The geology of the area between the Havelock and Msauli mines is not known in detail. According to Visser *et al.* (1956), the serpentinite is not a continuous body and is faulted out for at least part of its length. The Msauli serpentinite is itself located on a similar structural trend to an abandoned chrysotile prospect in the Steynsdorp valley (Van Biljon, 1959, and unpublished mining company reports; Fig. 1). There have been suggestions (e.g. Pretorius, 1961) that south of the Steynsdorp prospect the same asbestos-bearing "line" may reappear in Swaziland near Motjane (Fig. 1).

The area which includes the Havelock body has been mapped by the writer (Fig. 2). Field relations show that the

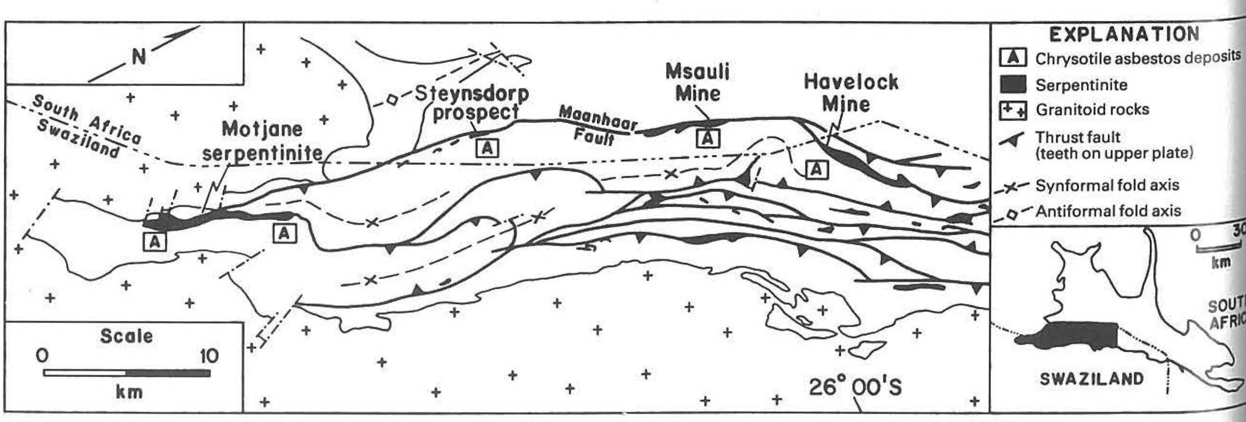

Figure 1

Simplified interpretation of the principal tectonic elements along the south-eastern edge of the Barberton greenstone belt (inset), showing locations of the Havelock and Msauli chrysotile asbestos mines, and the Steynsdorp and Motjane prospects. The Motjane serpentinite body contains antigorite in significant amounts, and uneconomic deposits of brittle chrysotile fibre. Structural data are based on the Swaziland Geological Survey 1:25 000 map series (Hunter and Jones, 1969; Urie, 1970, 1971) with modifications, and unpublished mining company reports. The fold structure west of the Steynsdorp prospect (Steynsdorp anticline) is taken from Viljoen *et al.* (1969, Fig. 2).

Havelock serpentinite is elongate in shape and closely aligned with the regional structural trend. For most of its length the serpentinite body is inclined at 45 to 70° toward the south or west.

Regional deformation in the area south of the mine has produced large refolded isoclinal folds. Axial surfaces of first-phase folds are sub-parallel to the margin of the ultramafic body, and to a single steep cleavage. Second-phase folds are open structures with no associated cleavage. Both deformations are recorded in talcose schists and volcaniclastic lithologies of the Onverwacht Group as well as in younger sequences that include banded iron-formation and shales of the Fig Tree Group.

The structural thickness of the Havelock serpentinite varies considerably. West of the mine, the serpentinite has been tectonically thinned by a steep fault along the southern edge of the body, and adjacent lithological units are clearly truncated by this fault. East and south-east of the mine, the serpentinite has been repeated by imbricate faults and the apparent structural thickness increased by the tectonic inclusion of rafts of country rock. Serpentinite adjacent to imbricate fault surfaces is extensively altered to talc.

The northern or footwall margin of the serpentinite is also a thrust surface, but it is not marked by a major talc zone of the type found within and along the southern edge of the body. Banded iron-formation in the immediate footwall is offset by transverse faults, but never obliquely truncated by the serpentinite. The history of deformation along the basal thrust appears to differ from other fractures associated with the serpentinite.

Large thrust faults and folded thrusts have been mapped for several tens of kilometres along the eastern edge of the greenstone belt north of the Havelock body (Hunter and Jones, 1968, 1969). There, the regional structure has been described in terms of a series of stacked thrust sheets that were emplaced toward the west or north-west (Barton, 1982). Though structural continuity with the serpentinite body has not been demonstrated, the basal thrust at Havelock is correlated with a movement horizon low in this tectonic stack.

A major tectonic break, known as the Maanhaar Fault, is closely associated with asbestos-bearing serpentinites in adjacent parts of KaNgwane. The Maanhaar Fault truncates the eastern limb of the Steynsdorp anticline (Viljoen *et al.*, 1969b; Fig. 1), but the position of the fault elsewhere, and the nature of its displacement have not been documented.

IV. MINE GEOLOGY

Vein chrysotile occurs within the dark green Havelock serpentinite in three distinct pale-green bodies (Urie, 1961; Fig. 2). Apart from the main producing ore body, only the Havelock West prospect, adjacent to the border with South Africa (KaNgwane), contains significant amounts of cross-fibre (fibre that occurs in seams oriented at a large angle to the seam wall).

A geological plan of the mine, and cross-sections representative of the main east and west ore shoots are shown in Figs. 3–5. Both ore body and non-fibrous serpentinites are inclined south at 50 to 60°; lithology and structure are described below in a traverse from north to south.

A. Footwall

Two very distinctive lithologies occur in the structural footwall of the Havelock body (Fig. 3). Nearest to, and in tectonic contact with, the serpentinite is a 35 to 40 m-thick unit of banded iron-formation. The basal member of the iron-formation is essentially unmetamorphosed, and iron is stored in carbonates (ankerite/ferroan dolomite and siderite) and, to a much lesser extent, in sulphides. Mineralogical observations show that close to the serpentinite, carbonate iron-formation is metamorphosed to oxide-silicate iron-formation (magnetite–minnesotaite–ferroactinolite). Metamorphic isograds parallel the base of the ultramafic slab, and are structurally inverted.

Exposures in the west of the mine (6W, Fig. 3), and exploration boreholes near 2E show the tectonic contact at the base of the serpentinite to be an irregular fracture which is locally oblique but generally sub-parallel to the layering in the iron-formation. Minor folds are present in the banded iron-formation close to the fault.

A narrow zone of amphibolite (<1 m wide) that contains antigorite–actinolite/tremolite–talc–magnetite, and chlorite (replaced in part by amphibole) occurs immediately below the tectonic break. Serpentinites above exhibit minor talcose alteration and contain shears filled with magnesite but no other mesoscopic foliation.

The structurally lowest unit exposed in underground development is a highly altered and pillowed mafic igneous sequence. Massive green and grey mafic lithologies with sharp internal contacts (inclined south at high angles) form the uppermost 30 m of the sequence. The contact with the banded iron-formation above is a sharp and irregular stratigraphic surface.

Pillow structures occur deeper in the footwall. Individual

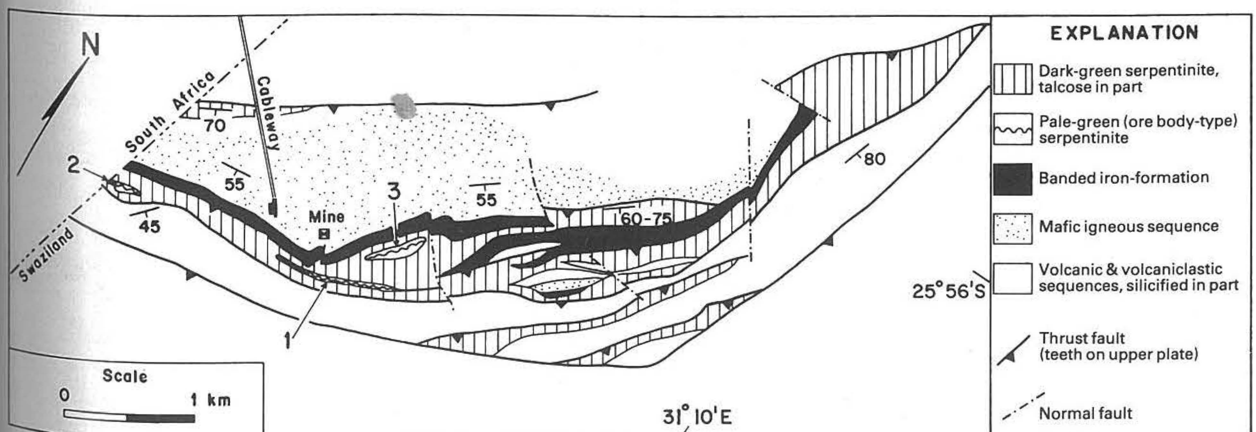

Figure 2

Geological map of the Havelock ultramafic body, based on mapping by the writer, with data from Urie (1961). Pale-green, asbestos-bearing serpentinite occurs within the Havelock body in three main areas: 1. Havelock ore body (see Fig. 3); 2. Havelock West prospect; 3. footwall body (slip-fibre only).

The Havelock complex is interpreted as an allochthonous serpentinite body that was emplaced along thrusts toward the north-west; tectonic slivers of serpentinite and talc schist are present south of the main body and are interpreted as thrust imbrications. The mafic volcanic sequence north of the basal serpentinite décollement attains its maximum stratigraphic thickness immediately below the producing ore body.

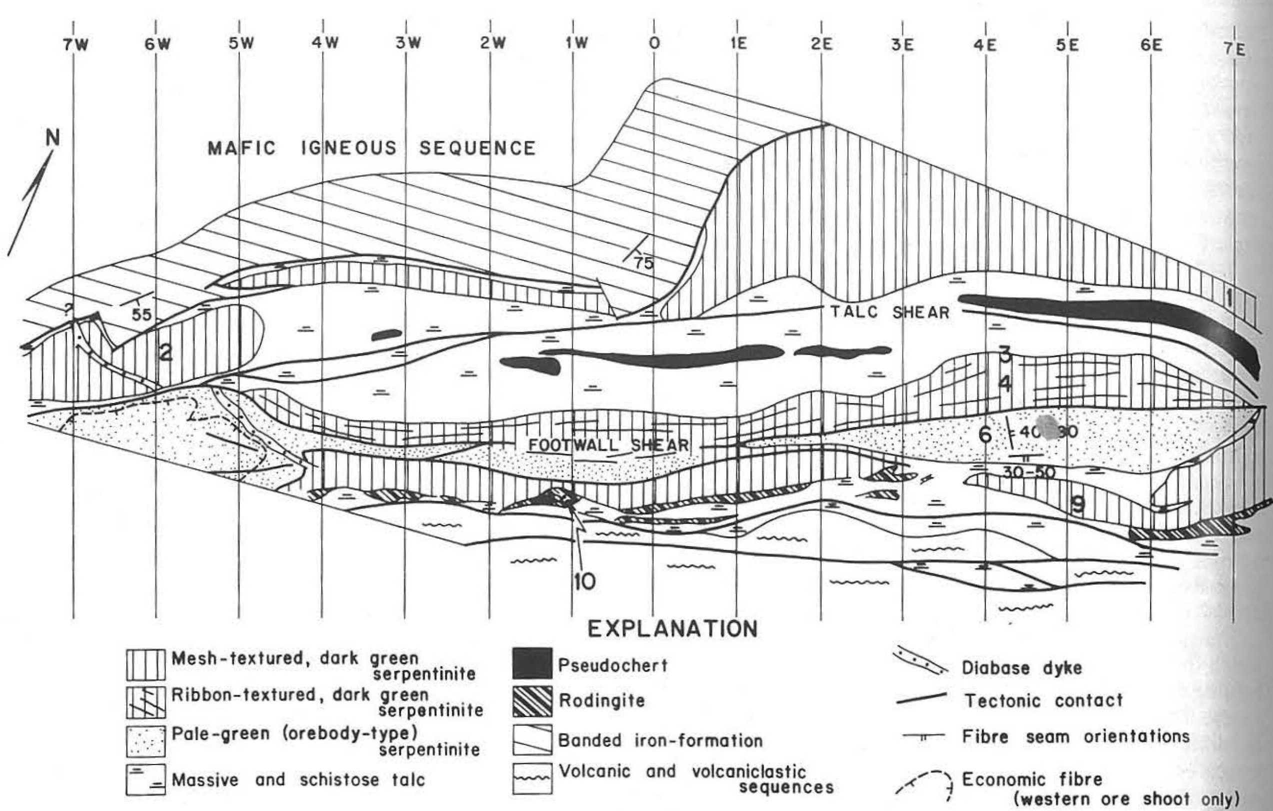

Figure 3

Plan of Havelock Mine geology at 390 Level (*c.* 400 m below outcrop); mining blocks are 60 m wide. Dark-green serpentinized dunite (with minor lherzolite) exhibiting mesh- and ribbon-textures occurs north of the footwall shear, and gives way to mesh-textured serpentinized harzburgite south of the ore body. Orientations of prominent fibre seam directions shown in the eastern ore shoot were measured on 315 Level. Chemical analyses of samples collected on or close to 390 Level (1–4, 6, 9–10) are listed in Table III.

pillows are pale green and contain abundant variolites. Broadly spherical pillows do occur, though elongate shapes are more typical, and a large variation in size is characteristic. Pillow margins are very irregular, and in places lobate.

Both massive and pillowed facies exhibit extreme alteration to carbonate (often >20 modal per cent). Original igneous phases are metamorphosed to albite–chlorite–ankerite/ferroan dolomite near the banded iron-formation, and oligoclase–chlorite–magnetite at depth (>150 m below the base of the banded iron-formation).

A full description and interpretation of the mineralogy and petrology of the Havelock banded iron-formation and mafic igneous sequence is given elsewhere (Barton, 1982). This work has shown that the altered and pillowed footwall unit is an extrusive sequence of broadly tholeiitic composition that has been subjected to a "spilitic metamorphism". The Havelock banded iron-formation rests on spilites of the same type that are widespread in ophiolite complexes and on the present-day sea floor.

B. Serpentinites and Related Rocks

East of zero section in Fig. 3, the footwall banded iron-formation strikes north away from the main ore body. The thickness of serpentinite increases rapidly, and includes an additional mass of pale-green serpentinite of the ore body type. Though the colour and texture are identical with the main chrysotile deposit, this pale-green footwall body is not known to contain economic fibre. Fibre that does occur is usually of the ribbon type, and where exposed underground (7E) it has a maximum length of 1,5 mm. There, the fibre is in closely spaced parallel fractures, and accounts for less than 1 per cent of the total volume.

In addition, borehole data near 2E show a 10 m-wide zone of 1 per cent brittle cross-fibre close to the footwall banded iron-formation. Unlike most cross-fibre at Havelock this fibre occurs in dark-green serpentinite.

One of the main features of the central and eastern mine geology is a major talc zone (Fig. 3). Where talc is schistose and oxidized by the circulation of meteoric waters, the trace of a fault (the talc shear) has been mapped. Massive talc is typical of the margins of the zone. In thin section, talcose lithologies contain conspicuous octahedra of magnetite.

The talc shear records an apparent 40 m left-lateral offset of a diabase dyke in the west ore shoot (Fig. 3). However, neither the relative age of dyke intrusion nor the complete displacement history of the talc shear are known with certainty. Near the dyke, chrysotile fibres lose their silky properties and no longer separate readily. This fibre deterioration is interpreted as the result of locally unfavourable conditions for chrysotile formation.

A discontinuous lithology known locally as "pseudochert" occurs within the eastern talc zone (Figs. 3 and 5). Pseudochert is composed of black glassy silica and contains pyrite and fractures filled with massive white quartz. Talc adjacent to the pseudochert is almost always foliated. Abrupt thickness variations occur both between levels (Fig. 5), and along the strike: at 7E the pseudochert is 17 m thick, but west of 3W on 390 Level it is absent.

The ore body serpentinite is described in detail below. Here it is noted that the serpentinite in the east footwall of the ore body is highly deformed and contains a coarse foliation inclined at 50–60° towards the south. As a result, the ground conditions for mining are particularly poor in the east footwall. In the west footwall, the serpentinite is massive, and the ore body appears to have taken up more of the deformation.

Almost none of the serpentinite exhibits compositional layering. A single 50 cm-wide orthopyroxenite dyke is known in the relatively undeformed west footwall. Between 4¾E and 5E (see sample locality No. 3, Fig. 3), serpentinite with an irregular streaking of opaque minerals forms the basal 4 m of the ore body footwall, immediately above the talc zone. A similar lithology also occurs at 2½E.

close to the footwall banded iron-formation. The possibility the serpentinites of this type are more extensively developed toward the base of the footwall serpentinite body (particularly east of about 5E) cannot be excluded since few exploration data are available from this area.

Finally, a lithology known in local mine terminology as the "hanging wall sill" occurs along the upper structural surface of the Havelock serpentinite (Figs. 3 and 5). The distinctive calcium-rich mineralogy, and a coarse or pegmatitic texture, make the hanging wall sill a useful marker horizon. It is interpreted here as a rodingite, and in common with rodingites described elsewhere (e.g. Coleman, 1967), it is thought to have formed by metasomatism during serpentinization.

Underground mapping and borehole data show that the hanging wall sill always occurs as irregular lenses and stringers (Figs. 3–5). Abrupt thickness variations to a maximum of 10 m are typical. Individual lenses are about 3 m wide and up to several tens of metres long. Inclusions of altered (talcose) serpentinite have been mapped in larger pods. Margins are irregular and frequently sheared; zones of cataclasis, orientated at high angles to the margin of the serpentinite, often terminate rodingite pods.

Rodingite mineralogy is variable: zoisite and tremolite (in the ratio 2:1) occur together with minor feldspars and calcite. Feldspars are replaced by, and enclose, large euhedral epidotes. In addition, minor chlorite, small (30 μm) radiating bundles of a mineral presumed to be prehnite, pods of cataclastic quartz, and patchy green amphiboles, which poikilitically enclose fresh albite, are present. Hydrogrossular has also been observed in Havelock rodingites (C. Frick, personal communication, 1979).

C. Hanging Wall

Underground development in the hanging wall is not extensive, and the description below is based on exposure between 1W and 5E (Fig. 3). There, a complex igneous and volcaniclastic pseudostratigraphy is present, which cannot be correlated along the strike with any certainty.

Massive and schistose talc, adjacent to the rodingites, extends into the hanging wall and rapidly gives way to a talc–colourless amphibole lithology. Long amphiboles (up to 5 mm) with sub-radiating habit, and a fine-grained talc matrix occur within 10 m of the serpentinite body. Textures of this type resemble metamorphosed dendritic and skeletal crystal forms that reflect rapid cooling from some magnesian liquids (spinifex-like textures).

Above, and in igneous contact with the talc–amphibole rock is a banded lithology with a volcaniclastic texture ("hanging wall chert"). This unit contains irregular iron-oxide coated fragments, mosaics of epidote, and deeply embayed quartz crystals (about 5 modal per cent). Elsewhere, the same lithology is almost totally silicified by microcrystalline quartz. The upper surface of this 20 m-thick unit is complex, and may represent a sheared igneous contact.

A deformed and metamorphosed mafic or ultramafic unit containing long (up to 30 mm) amphiboles is juxtaposed with the volcaniclastic lithology. Again, it resembles a unit with an original spinifex-like texture. Fragments of "pseudochert" and large tectonic blocks of talc schist occur within the sequence (Fig. 3), and suggest that the entire hanging wall has undergone extensive deformation.

V. DESCRIPTION OF THE ORE BODY

A. General Occurrence

Pale-green serpentinite is host to the vein chrysotile deposit. Both the colour, and a granular or sugary texture, distinguish the ore body from serpentinites that contain no fibre.

The transition from dark- to pale-green serpentinite is usually gradational. In the east footwall, the dark-green colour becomes progressively paler, the serpentinite texture progressively more granular, and a coarse foliation more pronounced. Broken ground to a maximum of 20 m true thickness is associated with a major structure known as the footwall shear (Fig. 3). Pale-green serpentinite, in and adjacent to the footwall shear, is highly fractured and extremely friable. Slip-fibre is smeared along many of the fractures, and the rock lacks cohesion and disaggregates in the hand.

The footwall shear forms the margin of the ore body in the eastern section of the mine. Farther west, fracture spacing and sometimes fibre length increase away from the footwall shear toward the ore body. As Fig. 3 shows, west of 5½W the footwall shear and main talc shear form a single fracture. There, the transition in colour from dark-green footwall serpentinite to pale-green ore body-type serpentinite is abrupt.

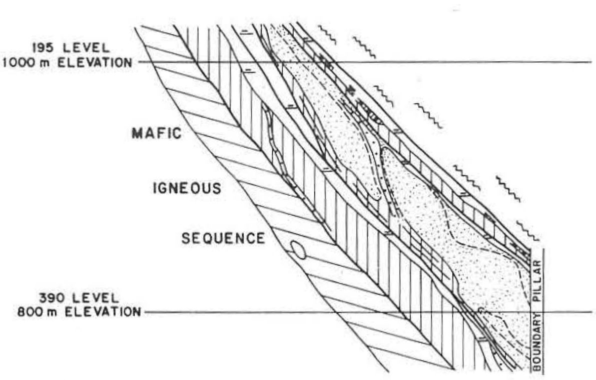

Figure 4

Cross-section at 5½ W, illustrating the main western ore shoot. Uneconomic fibre is encountered within the ore body at depth, and is shown enclosed by a broken line below 390 Level. For explanation see Fig. 3.

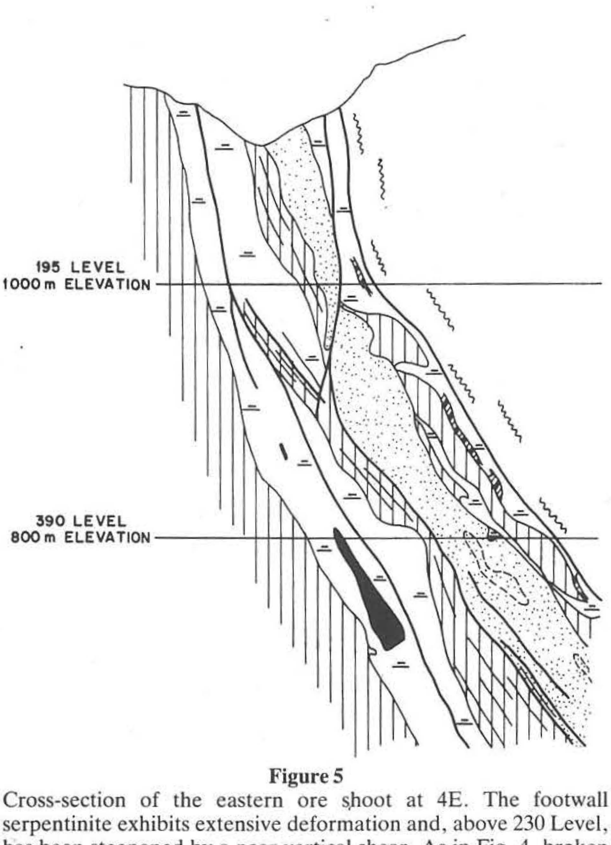

Figure 5

Cross-section of the eastern ore shoot at 4E. The footwall serpentinite exhibits extensive deformation and, above 230 Level, has been steepened by a near vertical shear. As in Fig. 4, broken lines within the ore body indicate massive, non-fibrous, pale-green serpentinite. Surface outline at 1975; for explanation see Fig. 3.

Gradational contacts occur along the edge of the ore body in the east hanging wall. Pale-green serpentinite gradually gives way to dark-green and eventually black serpentinized harzburgite. Though the colour changes are gradual, the decrease in economic fibre is rapid. Massive talc has replaced the ore body in the east hanging wall and complete talc pseudomorphs after chrysotile seams are well preserved. A hanging wall shear close to the upper surface of the ore body is only developed in the western section of the mine.

The colour of the ore body is not a uniform pale-green and appears to vary with depth below surface. In the upper abandoned mine levels, the ore body is a much paler (apple) green than that exposed in the lower levels. This relationship is also apparent when the considerably paler green waste dumps at the Msauli deposit are compared with those at Havelock. Msauli is a much more recent underground operation, and producing levels at the time of writing are still relatively close to the surface. Thus the colour of the ore body seems to be related, at least in part, to the present topography. It is noted that the main talc and footwall shears at Havelock are oxidized to at least 550 level, approximately 500 m below surface.

The average *in situ* fibre content of the ore body is about 5,5 per cent. Mean fibre length is difficult to specify because each grade produced at the mill (Turner and Newall grades 3, 4, 5 and 1877) includes a range of different sizes. A value of 4–5 mm is probably realistic for most fibre produced between 245 and 340 levels (250–350 m below outcrop).

Though fibre lengths of 60 mm have been recorded in the upper levels of the mine, spinning fibre is not a significant component of the ore body and there is very little short fibre. Both length and amount of fibre decrease with depth in the mine. In addition, the fibre is a better quality (silkier and paler in colour) in the ore shoot west of the dyke (Fig. 3).

Massive, non-fibrous serpentinite occurs within the ore body in the lower mine levels (Figs. 4 and 5). Uneconomic chrysotile of this type is a translucent green colour, and lacks the granular texture of the ore body. The sudden appearance of this massive material at depth also suggests that the total fibre content of the ore body decreases down-dip.

B. Geometry

A true thickness longitudinal projection of the ore body is given in Fig. 6; data from the upper levels (above 245 Level) in Fig. 6 are based on old records, and should be regarded as approximate. Thus, while the surface geological map (Fig. 2) shows the ore body schematically as a continuous unit, it may have cropped out as two or more lenses separated by faults. It is probable that faulting reduced the thickness of the ore body to 10 m or less near zero section (Fig. 6).

The total strike length of the deposit is at least 1 200 m, and as Figs. 4 and 5 show, the attitude is rather uniform (inclined at 50–60°) except east of about 2E and above 230 Level where it is near vertical. There, the ore body has been steepened by an oblique shear.

Maximum fibre development occurs at the two extremities of an elongated and broadly elliptical-shaped ore body (Fig. 6). At the edges of both ore shoots the thickness decreases rapidly. Talc has eaten away at the ore body in the east, and accounts for the reduced thickness in the vicinity of 315 Level. The geometry of the ore body below the boundary pillar is unknown.

It is emphasized that pale-green serpentinite is present in the centre of the mine, but that it is thin and highly sheared. A similar sheared lithology that carries less than 2 per cent of fibrous chrysotile is present in development immediately west of the mining lease area, and in the far west body adjacent to the border with KaNgwane (Fig. 2). Serpentinites of this type contain much of the chrysotile in the form of slip-fibre, that is fibres that are orientated parallel or at a very small angle to the seam wall.

Economic chrysotile occurs as a stockwork of cross-fibre seams. There is, however, a pronounced tendency toward sub-vertical seam orientations. Holes drilled through the ore body at 45° to the vertical are most likely to intersect fibre seams at large angles and are, therefore, the most useful for fibre evalutaion.

Structural measurements on 315 and 330 levels show that two seam directions are prominent within the stockwork. They are orientated at 1–17° and 78–89° to the strike (N 64° E) of the talc shear on 315 Level (Fig. 7). Fibre seam orientations at Havelock are predicted by the Coulomb criterion for simple shear failure associated with a direction and sense of shear close to that inferred for the main talc shear, assuming left-lateral strike-slip displacement (Fig. 7).

C. Fibre Morphology

Illustrated descriptions of chrysotile fibre seams from southern African asbestos occurrences have been made available by Van Biljon (1959) and Laubscher (1964, 1968). In addition, fibre seams which closely resemble the chrysotile at Havelock have been described from Canadian asbestos deposits by Riordon (1955) and Laurent (1975). The morphology of crystal fibres, in general, is given in Durney and Ramsay (1973), and though these authors did not describe chrysotile asbestos specifically, their data are also applicable to this mineral.

Chrysotile seams at Havelock are usually planar, but may be curved or irregular in shape. Individual fibres may be straight, crenulated, kinked or curved, but invariably join points on opposite walls that were once in contact. Slip-fibre is sometimes present within cross-fibre seams, usually along one wall. In these cases, movement parallel to the fibre length has displaced the opposite walls.

Single cross-fibre seams are most common, but more complex types with a single median suture or more than one line of wall rock inclusions often occur. The median suture usually varies in position and is not always located in the centre of the seam. Wall rock material that forms the median suture is either picrolite or magnetite. Picrolite is a splintery, pale-green variety of serpentine with a coarsely-fibrous texture (see Table II). A thin layer of picrolite and magnetite frequently separates wall rock and fibre along the length of the seam; it is also common parallel to fractures that contain no fibre.

The formation of crystal fibres by diffusion of fluids into dilating cracks has been described by Durney and Ramsay (1973). A similar mechanism is appropriate here, and is discussed below in more detail.

VI. SERPENTINITE TEXTURES

Two textural types are widespread within the Havelock body: a mesh-texture, in which the original protolith mineralogy can easily be recognized, and a ribbon-texture which records significant plastic strain.

Mesh- or replacement-textures are best preserved in the hanging wall serpentinized harzburgites, though they are also widespread in the west footwall and in the ore body. Serpentinized olivine grains are 300 to 2 000 μm in diameter, and in thin section appear as sub-equant grains often with a central "cross-hatched" core. Orthopyroxenes are totally serpentinized but retain a well-preserved cleavage and slightly higher birefringence. They have deeply embayed margins and poikilitically enclose serpentinized olivine grains. Where chrysotile fibre occurs, it is colourless, has lower relief and higher birefringence than the mesh-fabric. Fibre is always accompanied by an incipient ribbon-texture in serpentinized olivine grains.

Serpentinzed lherzolite at the base of the east footwall

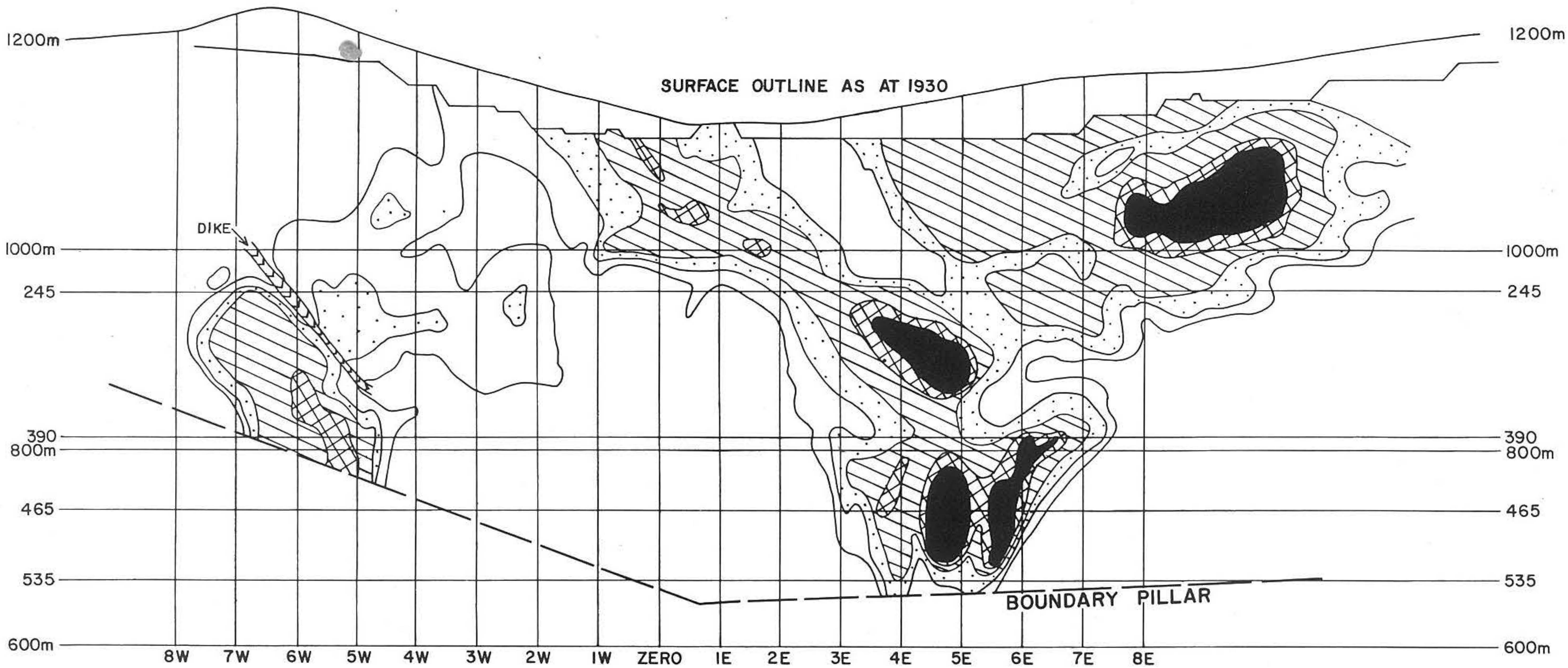

Figure 6

True thickness longitudinal projection of the chrysotile ore body; contours at 10, 20, 30, 40 and 50 m (black) thickness. True thickness is measured normal to the dip of the ore body at each elevation. Pale-green serpentinite is present in the centre of the mine, but is, for the most part, sheared and contains slip-fibre. The precision of data above about 245 Level is uncertain.

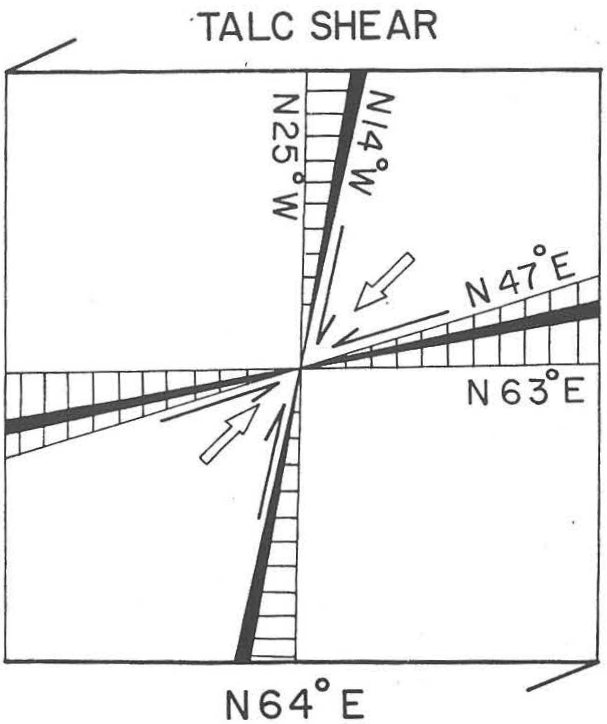

Figure 7

Measured fibre seam orientations (shaded angles) from the eastern ore shoot on 315 Level. The simplest interpretation of these data is that the fibre seams represent failure directions resulting from simple shear, as predicted by the Coulomb failure criterion for a material with a peak angle of shearing resistance ϕ, varying between 2 and 34°, and a direction of shear corresponding with the orientation of the talc and footwall shears on 315 Level (N 64° E). Black angles are the directions predicted by the Coulomb failure criterion for a material with $20° \leq \phi \leq 25°$, and the same direction of shear (see Tchalenko and Ambraseys, 1970). Other interpretations of the sense of movement on the talc and footwall shears are possible (see discussion in text).

contains a mesoscopic opaque streaking which in thin section consists of a series of narrow (50–1 000 μm wide) seams of fibrous serpentine that cut across a mesh fabric. Aggregates of magnetite are closely associated with these fibrous bands.

In the east footwall serpentinite, and near zones of relatively high strain within the ore body, the original mesh-texture has been destroyed. Instead, a series of parallel ribbons defined by alternating pale- and dark-grey (first order) interference colours are observed in thin section. Serpentinized olivine grains are obliterated, and identification of orthopyroxenes is difficult. Every transition occurs between colourless serpentinized olivine grains with broad (100 μm wide) ribbons, and highly deformed lithologies with ribbons less than 30 μm wide and considerable carbonate alteration.

Mesh-textures are common in lizardite serpentinites (e.g. Coleman and Keith, 1971), and in serpentinites that have not undergone significant plastic deformation (Raleigh and Paterson, 1965). Thus, regions where mesh-textures are present at Havelock record relatively small strains, and are more likely to preserve the original serpentinite mineralogy.

VII. SERPENTINITE MINERALOGY

A. Identification of Serpentine Species

Unambiguous identification of the serpentine minerals is difficult, and requires a combination of techniques. Table I summarizes the available Havelock data. Though Van Biljon (1959) interpreted Havelock as an antigorite body, his data are reinterpreted here on the basis of criteria described in detail by Mumpton and Thompson (1975). It is noted that the samples described by Van Biljon were collected near 155 Level (150 m below surface), and may not necessarily be representative of the ore body at depth.

Both massive and deformed serpentinites at Havelock are essentially lizardite–chrysotile mixtures. Trace amounts of antigorite were identified by differential thermal analysis.

B. Original Composition and Present Assemblage

The estimated variation in protolith composition of the Havelock ultramafic body is given in Table II. Olivine, orthopyroxene, chromite and minor clinopyroxene are original protolith phases; feldspar was not identified in any of the thin sections examined. Both footwall and ore body serpentinites are broadly dunitic in composition (less than 10 modal per cent orthopyroxene). The hanging wall consists of serpentinized harzburgite (11–24 modal per cent orthopyroxene), and accounts for the structurally uppermost 20 to 30 per cent of the ultramafic body.

Minor serpentinized lherzolite has been noted at the base of the east footwall (between $4\frac{1}{4}$E and 5E, Fig. 3), and in a narrow zone immediately above the footwall banded iron-formation (at $2\frac{1}{2}$E, Fig. 3). This lithology has a mottled appearance and exhibits an impersistent streaking of magnetite in layers 100 to 2 000 μm wide and 20 to 30 mm apart. The original modal composition is estimated as olivine 80 per cent, orthopyroxene 15 per cent and clinopyroxene ± 5 per cent. Clinopyroxene grains are fresh or only serpentinized in part.

Most serpentinites at Havelock contain significant amounts of brucite (Table II) though in some samples brucite is present in amounts considerably less than predicted by Hostetler *et al.* (1966), indicating that addition of silica or loss of magnesia was necessary. Sheared serpentinites of the east footwall contain less brucite than more massive equivalents.

TABLE I
Identification of Serpentine Species at Havelock Mine*

	Footwall	Ore Body			Hanging wall
	1	2	3	4	5
X-ray Diffraction	lizardite + chrysotile	chrysotile; some lizardite	chrysotile	chrysotile	lizardite; some chrysotile
Electron Microscopy	chrysotile; trace lizardite or antigorite	chrysotile	chrysotile	chrysotile	lizardite or antigorite; some chrysotile
Differential Thermal Analysis	chrysotile or lizardite; trace antigorite	chrysotile or lizardite	chrysotile or lizardite	chrysotile or lizardite; trace antigorite	chrysotile or lizardite; trace antigorite

* Based on data given in Van Biljon (1959).

Notes 1, 2 and 5 show persistent X-ray diffraction lines at 2,49 Å (lizardite); lines at 2,45 Å and 2,09 Å (chrysotile) are present in all samples (1–5). 1. deformed east footwall with brittle fibre; 2. ore body whole rock; 3. chrysotile fibre; 4. picrolite vein; 5. massive serpentinized harzburgite.

TABLE II
Mineralogical Composition of Havelock Serpentinites

	Estimated Original Composition			Present Modal Composition		
	Olivine	Orthopyroxene	Chromite	Brucite	Magnetite	Carbonate
East Footwall	94,5	5,5 (0,5–10,5)	0,1 (0,0–0,5)	7,4	1,5 (1,0–2,0)	1,5 (0,5–3,0)
West Footwall	94,0	6,0	0,1	13,4	0,9	0,3
Ore Body	93,0	7,0 (5,0–8,5)	0,0	9,6	2,0 (0,2–5,6)	8,0 (5,0–12,5)
Hanging Wall	86,0	14,0 (11,0–24,0)	0,3 (0,0–0,5)	15,5	0,8 (0,5–2,0)	0,5 (0,0–1,0)

Notes: all data except brucite in volume per cent from samples collected at or near 390 Level (numbers in parentheses represent range of compositions). Brucite values (weight per cent) are semi-quantitative, and determined on carbonate-free samples by a dilute acetic acid digestion described by Hostetler *et al.* (1966).

Magnetite is present in all Havelock serpentinites: in the ore body and east footwall, mesoscopic concentrations are present, often parallel with the margins of chrysotile seams. Coarse aggregates, composed of individual, 1 mm-sized octahedra are typical, and are especially prominent in pale-green serpentinites. In ribbon-textured serpentinites, magnetite aggregates occur parallel with the ribbon fabric. Though mesh-textured lithologies such as the hanging wall harzburgite appear to contain less magnetite (Table II), an equivalent amount may be present as a sub-microscopic dusting.

The effects of alteration are generally much more extensive in the ore body than either footwall or hanging wall serpentinites. Magnesite, accompanied by minor talc, increase in abundance with increase in deformation, and account for at least 20 per cent of the serpentinites close to the footwall shear. Because the degree of alteration varies considerably, the few carbonate determinations from 390 Level given in Table II may not be entirely representative of the ore body. Pale-green serpentinites from the surface and upper mine levels appear to contain rather more disseminated carbonates than at depth, though the present data are inadequate to state this with certainty. Semi-quantitative thermogravimetric determinations of chrysotile fibre show the following accessory minerals: 0,84 per cent brucite, 0,80 per cent magnetite, 1,71 per cent magnesite, 3,38 per cent talcose minerals (average of 17 determinations, unpublished report, Turner and Newall, Ltd).

VIII. SERPENTINITE AND RODINGITE CHEMISTRY

Several analyses of Havelock serpentinites and a single analysis of a rodingite are given in Table III. These geochemical data show that the serpentinites have a rather uniform refractory composition: they closely resemble ultramafic nodules, Alpine-type peridotites, and serpentinites dredged from the sea floor (Hess, 1964).

Havelock serpentinites have high H_2O^+ (10,9–15,0 per cent by weight), and with the exception of sample 3, low CaO contents (0,03–0,89 per cent), values consistent with 100 per cent serpentinization. The presence of minor unserpentinized clinopyroxene in sample 3 may account for the higher CaO content in that sample. In addition, Al_2O_3 contents are low (1,57–4,34 per cent), and TiO_2 and total alkalis are less than 0,17 and 0,27 per cent, respectively.

MgO/SiO_2 ratios of massive serpentinites in Table III (samples 2, 4, 6, 8 and 9) are consistent with values of serpentinized peridotites containing brucite, with 5 to 20 modal per cent orthopyroxene (Coleman and Keith, 1971). The ore body (sample 5) has a high MgO/SiO_2 ratio, which suggests either that the sample contained excess brucite, or that silica has been removed from the system. The value of 0,97 from the dunite of sample 1 is low. However, much of the footwall serpentinite body is deformed and MgO/SiO_2 ratios of sheared dunites decrease to values near unity (Coleman, 1971). Sample 3 has a MgO/SiO_2 ratio (0,89) typical of serpentinized lherzolites and consistent with the pyroxene mineralogy already described.

Representative total iron contents (recalculated as FeO) of totally serpentinized dunite and almost totally serpentinized harzburgite are given as 5,51 and 7,00 per cent, respectively, by Coleman and Keith (1971). Data in Table III show similar values (5,2–8,6 per cent) for the massive serpentinites, but anomalously low values for the sheared east footwall and ore body (samples 4–6). These three samples appear to be depleted in iron, possibly by as much as 1,5 per cent.

Serpentinization that accompanied deformation of the Havelock body was not isochemical. Deformed

TABLE III
Chemical Compositons of Havelock Serpentinites, Chrysotile Fibre and Rodingite

	1	2	3	4	5	6	7	8	9	10
SiO_2	36,76	37,23	39,31	37,92	33,82	35,59	39,96	36,91	37,42	28,32
Al_2O_3	3,10	3,42	4,34	2,71	1,57	2,02	0,85	3,52	3,16	20,60
FeO*	8,61	5,36	6,70	4,23	3,59	4,53	3,37	6,32	5,21	5,88
MgO	35,84	38,58	34,79	39,68	44,49	41,50	40,66	39,07	38,64	14,94
CaO	0,89	0,03	3,35	0,12	0,10	0,09	0,24	0,36	0,24	17,27
H_2O^+	12,86	12,86	10,89	13,54	15,05	14,59	12,67	12,66	13,18	12,29
H_2O^-	0,38	0,50	0,21	0,31	0,47	0,52	0,79	0,34	0,29	0,14
Cr_2O_3	0,20	0,27	0,27	0,26	n.d	0,40	n.d.	n.d.	0,57	0,09
Total	98,64	98,25	99,86	98,77	99,09	99,24	98,54	99,18	98,71	99,53
MgO/SiO_2	0,97	1,04	0,89	1,05	1,32	1,17	1,02	1,06	1,03	

* Total iron expressed as FeO; n.d. = not determined

Notes: 1–2. footwall serpentinized dunites with mesh-textures, 390 Level; 3. serpentinized lherzolite, 390 Level; 4. serpentinized dunite with ribbon-texture, 390 Level; 5. ore body, 155 Level; 6. ore body, 390 Level; 7. chrysotile fibre, 155 Level; 8. hanging wall serpentinized harzburgite, 155 Level; 9. hanging wall serpentinized harzburgite, 390 Level; 10. rodingite, 390 Level.
Samples 5, 7 and 8 taken from Van Biljon (1959); all other analyses performed by the Geological Survey, Pretoria (see Fig. 3 for sample locations).

serpentinites contain less iron, silica and alumina, and more magnesia and water than their undeformed equivalents.

Chemistry of the "hanging wall sill" (sample 10) is qualitatively similar to that of rocks described elsewhere as rodingites (Coleman, 1967; Honnorez and Kirst, 1975). Enrichment in H_2O^+ and CaO, and depletion in SiO_2 are characteristic of rodingites. Rodingites similar in composition to those described here have been reported from the equatorial mid-Atlantic fracture zones by Honnorez and Kirst (1975).

IX. INTERPRETATION

A. Origin of the Ultramafic Body

Were the Barberton greenstone belt not so closely associated with the occurrence of igneous rocks that crystallized from ultramafic magmas, one would have little hesitation in describing the Havelock body as an Alpine-type serpentinite. Structural relations show that the serpentinite is associated with a major tectonic break (Fig. 1). It is an elongate, mesh-textured, lizardite body with faulted margins and associated rodingites. Serpentinites of this type are known elsewhere as Alpine-type serpentinites, and have been widely described from many younger orogenic belts. The assemblage lizardite–chrysotile–brucite–magnetite is consistent with the majority of Alpine-type serpentinites (Coleman, 1971).

However, volcanic and sub-volcanic rocks derived from melts that contained over 30 per cent MgO are not considered unusual in the Barberton area. Therefore, the hypothesis cannot be rejected that the Havelock body represents an ultramafic sill, either because of the bulk composition, or from structural evidence alone. Indeed, in an area where deformed stratigraphic sequences of ultramafic composition have been described (Viljoen and Viljoen, 1969a), it may not be easy to distinguish in the field between a mantle- and crustal-derived serpentinite. Here it is noted only that the Havelock body does not exhibit several of the features normally associated with high-level floored intrusions.

Chemical data show that the unaltered Havelock serpentinites contain 35 to 40 per cent MgO (Table III). Dunites and harzburgites with these compositions could have formed after relatively small amounts of fractionation of a periodotitic liquid. However, if gabbros or similar differentiates once existed they are now missing, and the reason for this absence is unknown.

Compositional layering is also conspicuously absent. Compositional layering itself is not necessarily indicative of magmatic processes, and in Alpine-type peridotites may be largely deformational in origin (Thayer, 1963; Dick and Sinton, 1979). Features that do characterize magmatic sediments include cryptic variation and progressive changes in composition. It is recognised, however, that serpentinization may have obscured such features at Havelock.

The nature of the original compositional change from dunite (<10 modal per cent orthopyroxene) in the Havelock footwall and ore body, to harzburgite (24 modal per cent orthopyroxene) in the hanging wall is interpreted in terms of fractional crystallisation dominated by the separation of olivine. Progressive changes in mineralogy of this type are often associated with magmatic cumulates, and are known in ultramafic rocks emplaced by tectonic processes (e.g. Page, 1967). Cumulus sequences form an integral part of many tectonically emplaced ultramafic bodies such as ophiolites. A comparison of the clinopyroxene and chromian spinel compositions at Havelock with those described from metamorphic peridotites and layered intrusions elsewhere may provide less ambiguous evidence.

Harzburgite textures at Havelock resemble those described in ultramafic rocks formed by igneous processes, either in layered intrusions or as part of a cumulus sequence within a tectonically emplaced body. However, qualitatively similar embayed pyroxene textures from an Alpine-type peridotite have been interpreted in terms of deformation processes (Dick and Sinton, 1979). The interpretation of textures in fresh ultramafics is not straightforward, and in serpentinites is equivocal at best.

It could be argued that those lithologies in the structural hanging wall, that exhibit spinifex-like texture, represent a chilled border facies to the ultramafic body. It is apparent from surface and underground mapping that while talcose schist with elongate-shape tremolite occurs locally in tectonic contact with the serpentinite, the same lithology elsewhere is either absent or contained *within* the hanging wall sequence. Therefore, though possibly related in some way to the occurrence of magnesian liquids, this lithology in no way resembles a continuous chilled border. The absence of such a border facies along both margins of the Havelock body is consistent with tectonic emplacement.

Narrow zones of amphibolite and structurally inverted metamorphic aureoles of the type described briefly from the Havelock footwall are present at the base of several obducted slabs of ophiolite (see review by Coleman, 1977). The formation of such metamorphic zones is usually considered to result from the downward conduction of heat from the overlying slab, or shear heating at the fault or some combination of these processes (Graham and England, 1976; Woodcock and Robertson, 1977).

B. Origin of the Asbestos

Internal deformation of the serpentinite, and formation of the chrysotile ore body appear to have been synchronous. A zone of ribbon-textured serpentinites occurs along one margin of the ore body. Foliation surfaces within this zone are parallel or sub-parallel to the length of the ore body, and to the talc and footwall shears. Well-preserved mesh-textures only occur toward the edge of the serpentinite, and are thought to record rather smaller strains.

The chrysotile ore body exhibits evidence of deformation by pressure solution–diffusion processes. Analogy with textures described for fibrous growth by Durney and Ramsay (1973) suggests that chrysotile asbestos fibres are syntectonic phenomena, and that growth was synchronous with progressive fissure dilation. At Havelock, fibre length (the amount of dilation) decreases with depth in the mine.

Other observations, particularly the hydrated and carbonated nature of the ore body, and the presence of linear talc zones that contain elongated pods of silica (pseudochert in Figs. 3 and 5) are consistent with massive circulation of fluids. The broadly tabular shape of the ore body, and the fault-like geometry of the talc zones, indicate that fluids travelled along structural surfaces parallel with the margins of the serpentinite body. The degree of ore body hydration and the extent of talcose alteration also decrease with depth below surface and suggest a decrease in fluid activity in this direction.

Pressure solution processes and the extent of fluid motion together account for the observed distribution of magnetite within the pale-green ore body. Magnetite occurs in concentrations parallel with fibre seams, and forms progressively coarser aggregates as serpentinites become progressively hydrated and paler in colour. Down-dip colour variations from pale- to dark-green within the Havelock ore body can thus be readily explained in terms of migration of magnetite during deformation and serpentinization. The effects of any alteration superimposed by late or even present-day meteoric fluids is unknown.

Raleigh and Paterson (1965) noted that the serpentinites, visibly damp at the end of their high temperature experiments, were also paler in colour. Unlike the experimental material, textural and mineralogical observations show that there is no evidence for dehydration reactions in the Havelock ore body. It appears that in some tectonic environments, significant movement of pore fluid can occur in serpentinites at temperatures less than dehydration.

Though geochemical data are rather sparse, the low Fe, Si and Al-contents of hydrated and deformed pale-green serpentinites suggest that formation of the chrysotile ore body was not an isochemical process. Evidence that supports this suggestion is described elsewhere (Barton, 1982).

Two explanations satisfactorily account for the formation of the asbestos ore body in terms of deformation during faulting:

1. Deformation recorded by the ore body is consistent with a regime of *strike-slip faulting* that occurred during or after the tectonic event that turned the regional stratigraphy on edge.

The simplest interpretation of the mine geology is that the diabase dyke in the western ore shoot records the total offset along the talc and footwall shears. The dyke trend is not consistent with intrusion in a tectonic stress regime of left-lateral strike-faulting of the type inferred from the orientation of chrysotile fibre seams (see Fig. 7). Internal deformation of the serpentinite and formation of the asbestos ore body are thus consistent with relatively small (40 m or less) strike-slip fault displacements.

Dilatancy and fluid diffusion processes are widely believed to occur along several presently active strike-slip faults (for example, the San Andreas Fault), especially in those regimes where tectonic stress has risen to relatively high levels (Nur, 1972; Scholz *et al.*, 1973). A dilatancy-fluid diffusion model is thought to account for anomalous changes in water flow and other physical parameters that occur prior to some present-day shallow earthquakes. The model assumes that the opening of dilation cracks results in an increase in pore volume, which itself induces fluid diffusion. The pressure of pore fluid gradually increases during diffusion and effectively reduces the frictional resistance until an earthquake is triggered.

The ore body at Havelock is close to a fault with an apparent strike-slip offset, and may have formed during the deformation that accompanied fault movement. Dilatancy within the ore body appears to have been largely rate controlled by diffusion. It is possible, therefore, that the formation of the asbestos deposit was accompanied by ancient seismic faulting.

2. Deformation associated with emplacement of the serpentinite is consistent with a regime of *thrust faulting*. Structural relations and the distribution of asbestos also indicate a pattern of strain that developed within the toe of a thrust sheet.

The autochthonous (or para-autochthonous) mafic volcanic sequence has a pronounced lenticular shape and attains its greatest stratigraphic thickness (± 1 km) immediately below the ore body. One consequence of an irregular-shaped unit of this type appears to have been extensive repetition by faulting in the region where the serpentinite was driven across the south-eastern side of the volcanic pile (Fig. 2). For this reason, deforming stresses close to the ore body could have accumulated in response to movement along an irregular décollement at the base of the Havelock body. Reverse faults and internal deformation of the serpentinite body could be interpreted as the hanging wall expressions of a non-planar basal thrust surface.

The model assumes that the talc and footwall shears are thrust faults initiated in the mechanically weakest serpentinites (dunites rather than harzburgites). Dip-slip displacements of ± 100 m could account for the dyke offset at the base of the western ore shoot. In such an interpretation, maximum dilation and the formation of asbestos ore bodies would take place above the footwall shear in the upper thrust plate.

Progressive deformation of the serpentinite body during faulting resulted in the eventual leakage of pore fluid through fractures, including some opened hydraulically. Dilatancy, fluid diffusion and the eventual destruction of the cohesive strength of the serpentinite were followed in turn by the circulation of talc-forming fluids parallel with fault surfaces.

Field observations are consistent with both of the above models. Structural and stratigraphic evidence for regional telescoping demonstrates that one or more regimes of thrust faulting have operated in the Barberton area in the past. However, the orientations of fibre seams, together with evidence that indicates the *ore body* formed in a high-level crustal environment are more readily explained in the first model.

X. SUMMARY AND CONCLUSION

1. The Havelock ore body is a vein chrysotile deposit within the centre of an allochthonous and almost totally serpentinized dunite–harzburgite. Olivine, orthopyroxene, chromite and minor clinopyroxene are original protolith phases; plagioclase was not identified in any of the thin sections examined. The primary serpentinite assemblage lizardite–chrysotile–brucite–magnetite is present, and it is probable that trace amounts of antigorite also occur. Lizardite is common in Alpine-type serpentinites, and is stable in all serpentinites at low grades of metamorphism (Coleman, 1971).

2. Major element chemistry of the undeformed Havelock serpentinites reveals rather depleted compositions. Ultramafic rocks with a comparable chemistry include tectonically emplaced metamorphic peridotites described from younger orogenic belts, and serpentinites that are forming today in oceanic fracture zones (Miyashiro *et al.*, 1969). Refractory compositions that characterize ultramafic rocks of this type are widely believed to represent residual mantle material. Similar compositions may also characterize ultramafic rocks that occur early in the greenstone belt succession and represent "residual" crustal material.

3. Internal mineralogical variations within the Havelock body are conspicuously lacking. There are no compositional layers or gabbroic lithologies, both of which are ubiquitous in floored intrusions. An increase in orthopyroxene content from serpentinized dunites in the footwall and ore body, to serpentinized harzburgites in the hanging wall is comparable with variations of the type that characterize magmatic cumulates. Other evidence that magmatic processes have operated, such as cryptic layering, has not been observed. Almost certainly, evidence of this type would be difficult to recognize in a deformed and almost totally serpentinized ultramafic body llike Havelock.

4. Rodingites occur as discontinuous lenses along the faulted southern contact of the serpentinite. The calcium-rich mineralogy is consistent with metasomatism by Ca^{+2}–OH^{-1}-type fluids during serpentinization (Barnes *et al.*, 1967; Barnes and O'Neil, 1969). The association between rodingites and the tectonic margins of serpentinites is well known (Coleman, 1967).

5. Structural relations and the absence of mafic differentiates suggest that the Havelock body was not emplaced into its present position by magmatic processes. Rather, the evidence is consistent with emplacement during tectonic activity. It is not known whether the serpentinite is highly allochthonous or derived locally from the ultramafic succession of the greenstone belt. Thus, the original suggestion by Viljoen and Viljoen (1969b, c) that the Havelock body represents a fragment of a sill may be correct, though their contention that the serpentinite occupies a stratigraphic horizon is disputed. The

stratigraphy of the eastern margin of the Barberton greenstone belt proposed by these authors is clearly inappropriate since it does not allow for the effects of deformation.

6. Though both contacts of the serpentinite are tectonic, significant plastic strain is only recorded away from the margins, within the centre of the body. Increasing strain is recorded as the progressive destruction of mesh-textures. Neocrystalline olivine is absent, and this absence suggests that the ribbon-textured serpentinites developed in a low temperature environment of relatively rapid stress accumulation where the pore fluid pressure could not be maintained at the equilibruim value.

7. The morphology of vein chrysotile in the Havelock deposit is closely comparable with the syntectonic fibres described by Durney and Ramsay (1973). It is suggested by analogy that much of the fibrous chrysotile was derived from the surrounding rock by diffusion, and redeposited synchronously with incremental fissure dilation. The diffusion gradient may have been the result of increased pore volume that accompanied dilating cracks. In the ore body, dilatancy and diffusion took place at temperatures below dehydration. According to experimental data, dehydration of mesh-textured lizardite serpentinites occurs in the 300 to 350 °C temperature range (Raleigh and Paterson, 1965).

8. It is suggested that the ore body formed in the uppermost levels of the crust during deformation associated with a strike-slip fault regime. Field observations in Swaziland indicate a correlation between the distribution of deformed and extensively hydrated pale-green serpentinites, and regions of complex faulting.

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