A REVIEW OF ASBESTOS RESOURCES

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This dissertation was prepared in accordance with specifications laid down by the University and was completed within a period of ten weeks of full time study.

TO

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Without whom this year would
not have been possible.

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INTRODUCTION

Asbestos is a commercial name applied to a number of incombustible fibrous silicate minerals. These minerals all have the common ability to be separated into relatively soft, silky and flexible fibres. Essential industrial requirements for the various types of asbestos are a fairly high tensile strength, resistance to heat, acids and chemical solutions.

Fibrous forms of serpentine and amphibole comprise this group of minerals. Chrysotile is the only fibrous mineral within the serpentine group and constitutes approximately 95% of world asbestos production. There are six asbestiform amphibole minerals, namely: crocidolite, amosite, anthophyllite, tremolite, actinolite and potassium richterite. Only the latter two are of little economic importance. Crocidolite and amosite are the dominant amphibole asbestos minerals and constitute nearly all of the remaining 5% of world asbestos production. There is minor anthophyllite and tremolite production.

Asbestos is a major industrial mineral used in a wide range of products. The single greatest use is in asbestos cement products where asbestos fibre is used as an additive to increase the strength and/or flexibility of the product. The production of vinyl floor coverings is another major use of asbestos. Paper and millboard made with asbestos are used as roofing felt, pipe coverings and electrical insulation among other products. Asbestos is used in brake linings, clutch plates and other friction material; in asbestos textiles which are used in the electrical industry and as felts for resin laminates. Asbestos is also used in the production of gaskets, various asphalt products, paints, putties, joint fillers, caulking compounds, and as reinforcing in plastics (Wicks, 1980).

The physical and chemical properties of the asbestiform minerals can be directly related to their crystal structure and chemical composition. These properties also influence their commercial importance.

Chrysotile is a variety of serpentine, being a hydrous silicate of magnesium, $Mg_6((OH)_4\ Si_2O_5)_2$. The colour is pale green, yellow or grey, but when opened up the fibres appear white and in commence it is termed "White" asbestos.

Its two most important characteristics are resistance to heat and suitability for spinning and weaving in much the same way as cotton, silk or wool. Chrysotile fuses at a high temperature but it loses most of its combined water around 650°C and becomes brittle. Spinnability depends on the length of the fibre, flexibility and tensile strength. Chrysotile fibres from different deposits and even from the same mine often differ greatly in such properties as tensile strength and resilience. Such variations in quality are typical of all varieties of asbestos. Chrysotile, unlike crocidolite and amosite, is readily decomposed by hydrochloric acid.

Chrysotile is most commonly used for asbestos textile, brake-linings and clutch-facings, asbestos boards, insulation products and asbestos-cement products. For the last use harshness is desirable; the different qualities of chrysotile fibres possess this property in differing degrees and in this respect chrysotile is generally inferior to amosite and crocidolite.

The largest producers of chrysotile are Canada, Russia and Zimbabwe. The latter produces a low-iron chrysotile which is valued as an electrical insulating material, especially in ships.

Crocidolite is known as "Blue" asbestos because of its characteristic blue colour. Its approximate chemical formula is $Na_2Fe_5((OH)Si_4O11)_2$. Crocidolite is characterized by high tensile strength, acid resistance, and harshness in wet mix; it fuses more readily than chrysotile and at about 360°C it loses most of its combined water and its tensile strength. Long-fibre crocidolite is woven into fabrics used for locomotive boiler lagging and for acid-resistant packings and gaskets. The principal use of the shorter crocidolite fibres is in making asbestos-cement pipe. Long blue fibres are exceptionally well adapted for gas-mask filters and Bolivian crocidolite is preferred for this purpose.

In South Africa, Transvaal Blue differs mainly from Cape Blue in that it generally contains small and varying amounts of minute magnetite crystals which cut the fibres; Transvaal crocidolite also contains varying amounts of amosite and does not fiberize quite as readily as the Cape material. Improvements in milling methods are largely overcoming these adverse factors.

South Africa is the dominant producer of crocidolite; the only other producer is Western Australia where a blue fibre comparable in quality with Cape Blue is produced. Blue asbestos from Bolivia is of inferior quality and there is little demand for it on the world market.

Amosite is a member of the grunerite-cummingtonite series of minerals and is composed essentially of ferrous silicate with small quantities of magnesia, alumina, ferric iron and water; chemically it resembles crocidolite and can be used for similar purposes in industry. The colour is yellowish-grey to white. Amosite fiberizes readily and is harsher than chrysotile in spinnability and tensile strength. It is similar to crocidolite, but it possesses a great advantage over other types of asbestos in that it is unsurpassed in regard to length of fibre. Lengths of 7,5-15 cm are common but the range is from a fraction of a millimetre to about 33 cm. Its resistance to acids and seawater is much greater than that of chrysotile and it fuses at a higher temperature than crocidolite.

Amosite is used for felted insulation in blanket form for high-temperature service up to 480°C; a composition of 85 per cent basic magnesium carbonate together with amosite and chrysotile is used for block and pipe insulation at lower temperatures. In loosely compacted form amosite is applied as a covering for marine turbines, jet engines and similar applications because it does not pack under vibration and, if it becomes wet, it dries without detriment to the product. Another special use for amosite is for making a lightweight fireproof wallboard used for partitions in ships. Amosite is produced only in South Africa.

Tremolite is a calcium-magnesium amphibole that is usually found as long, light-coloured but sometimes grey, silky fibres which lack strength and are consequently unsuitable for spinning. Anthophyllite is a rhombic iron-magnesium hornblende. It is light in colour, brittle, and has a low tensile strength and a relatively weakly developed fibre structure.

Tremolite and anthophyllite are used for chemical-resistant filters, as welding-rod coating, and as fillers in various products.

Potassium richterite is a fibrous amphibole found in siliceous dolomite in minor quantities. Fibres are silky, with good tensile strength and a low iron content, which is suitable in the electrical industry.

Chrysotile asbestos occurs in two different geological settings: as veins in serpentinized ultramafic rocks; as veins in thin layers of serpentinized dolomitic limestones.

Crocidolite and amosite occur only in certain fine-grained cherty ferruginous metasediments of the sort commonly named "banded ironstones". The banded iron formations in which the crocidolite occurs are distinctive in that aggregates of sodium-rich minerals are found in certain layers. Such geologic settings are known in only a few localities in the world and in still fewer places have geologic processes resulted in the formation of crocidolite and amosite.

Anthophyllite and tremolite occur in ultramafic intrusions and in associated greenstone and amphibolite, but the deposits are small and erratic in distribution (Coetzee et al., 1976).

Asbestos occurs as cross-fibre veins in which the fibres are parallel and normal to the vein walls, as slip-fibre in which the fibres lie in near-parallel arrangement often somewhat matted together along the plane of the vein, which is commonly an obvious plane of slippage, or as mass-fibre which is an aggregation of variously oriented fibres or stellate groups of radially arranged fibres. Most cross-fibre veins are split by one or more partings about parallel to the vein walls and these fibres are therefore considerably shorter than the vein width. Cross-fibre asbestos is the type which is most readily separated from the enclosing rock. Slip-fibres may be of considerable length and flexibility, but commonly present difficulties in preparation. Chrysotile, crocidolite and amosite occur mainly as cross-fibre; however, some slip-fibre is found in most chrysotile deposits. Anthophyllite, tremolite and actinolite occur mainly as mass-fibre or slip-fibre; they are least amenable to separation and are commonly brittle or weak and therefore limited in use.

The term vein is commonly used to designate a layer of chrysotile asbestos. The corresponding term applied to crocidolite and amosite deposits is generally band or seam and denotes layers which are conformable to the bedding planes of the banded iron formation. A group of asbestos bands which can be mined together as a unit is called a reef. In the case of crocidolite and amosite a group of reefs lying near to one another but separated by layers of barren rock of varying thickness is called a zone or horizon. These occupy a specific stratigraphic position, generally have a true thickness of 30-60 m and consist of up to 10 separate reefs, each of which contains numerous bands of fibre (Coetzee et al., 1976).

The Crystal Structure

Chrysotile asbestos has a layered-type crystal structure. The basic structure of serpentine is composed of a tetrahedral sheet, coupled through apical oxygens to an octahedral sheet (Wicks, 1980). The tetrahedral sheet is composed of silicon tetrahedra, Si_2O_5, forming an inner layer. The octahedral sheet is composed of brucite, $Mg(OH)_2$, forming the outside layers of a double sheet (Fig. 1.1). These sheets form the fundamental fibrils of chrysotile asbestos (Speil and Leineweber, 1969).

The octahedral sheet is larger than the tetrahedral one which introduces a strain in the structure causing curvature of the fibrils (Winson, 1975; Mann, 1981) and creates a mismatch leading to the three basic structural variations of the serpentine group : lizardite, antigorite and chrysotile. Lizardite has a planar structure formed by alternating compression and stretching of the sheets to overcome the mismatch. Antigorite has a continuous alternating wave or corrugated structure whereas in chrysotile the layers curve around to form either a concentric cylindrical structure (Fig. 1.2 a) or a continuous spiral (Fig. 1.2 b). This cylindrical

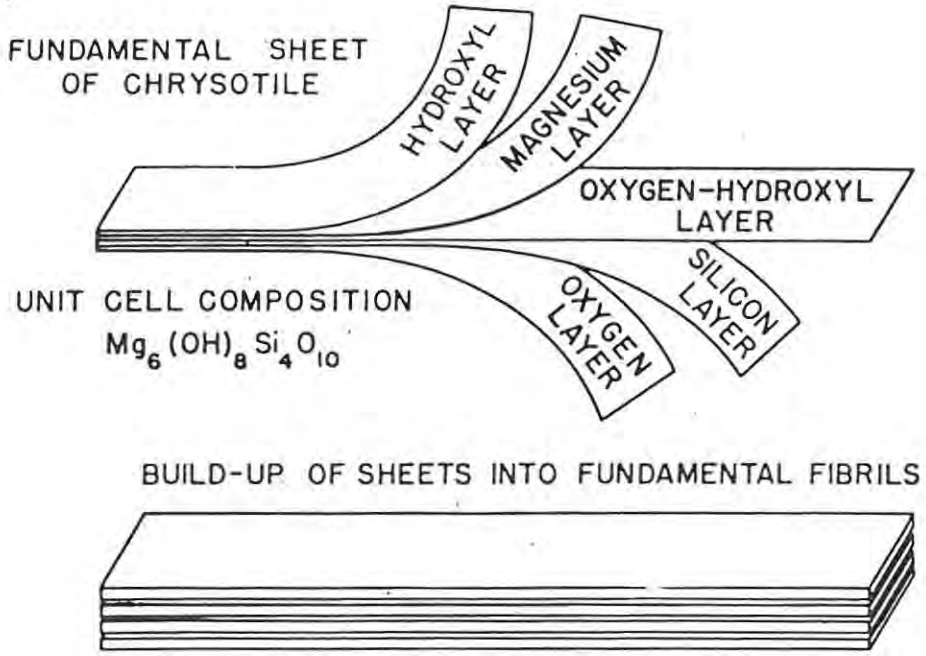
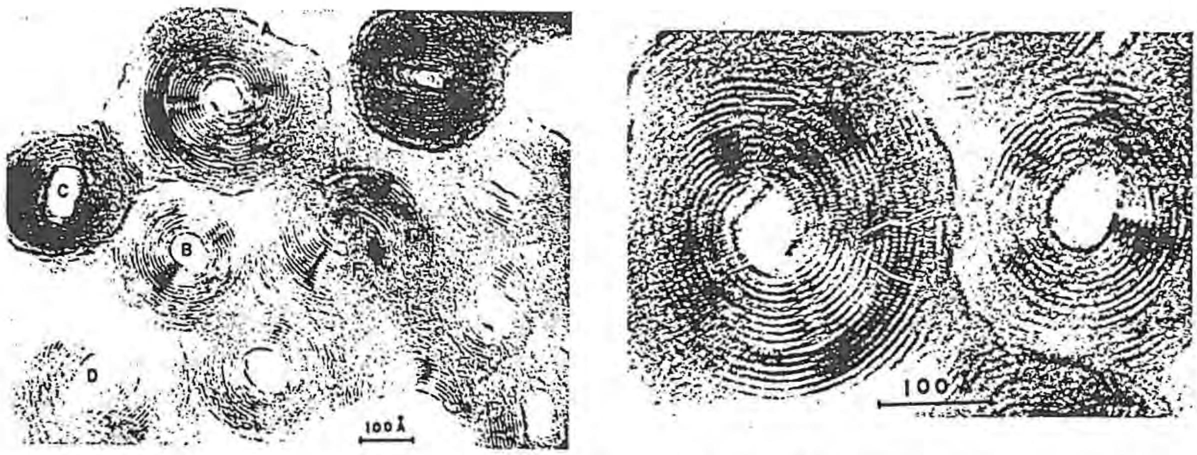


Figure 1.1: Chrysotile asbestos layered-type crystal structure comprising layers which form a fundamental sheet of chrysotile. (Speil and Leineweber, 1969)



a: Concentric growth structure b: Spiral growth structure

Figure 1.2: The hollow cylindrical structures of chrysotile fibrils shown by high resolution electron microscopy. (after Yada, 1967).

structure produces the fibrous properties of chrysotile asbestos (Wicks, 1980), making it soft and flexible. The longer fibre is thus suitable for spinning into textile-type products.

Yada and Iishi (1975) studied the micro-structures of synthetic chrysotile and lizardite by using high resolution electron microscopy. They confirmed a conical or cylindrical fibril shape comprising membrane layers which are formed from the serpentinization of olivine. Three types of chrysotile structures: clino-, para- and ortho- chrysotile were also confirmed by X-ray analysis and electron microscopy (Yada, 1971; Middleton and Wicks, 1975; Shao-Ying et al., 1980). The latter workers have shown that chrysotile asbestos fibrils from serpentinized dolomitic rocks also have cylindrical and helical structures. Detailed studies have been carried out on Canadian and Zimbabwean chrysotile fibre and it was found that the mean fibril diameters of the longer spinning grades are larger than those of the corresponding shorter grades (Atkinson et al., 1971). This larger diameter increases the fibril flexibility necessary for textile- type products.

The basic amphibole asbestos crystal form is a double silica chain, Si_4O_{11}, separated by a band of seven cations with two hydroxyl groups attached to the central cation of each unit cell. These stack together to form a sandwich of ribbons in the final structure with a marked cleavage developed between the ribbons (Fig. 1.3).

Chemical Composition

The theoretical chemical compositions of six of the types of asbestos are given in Table 1.1. The basic structure of the five amphibole minerals is the same, only with differing amounts and types of metallic cations. Consequently all the amphiboles are quite similar but do differ substantially from chrysotile.

Type	Theoretical Formulae
Chrysotile Hydrated magnesium silicate	$Mg_6[(OH)_4Si_2O_5]_2$
Crocidolite Complex sodium iron silicate commonly called Blue Asbestos	$Na_2Fe_5[(OH)Si_4O_{11}]_2$
Amosite Iron magnesium silicate—same as anthophyllite except for high iron content	$MgFe_6[(OH)Si_4O_{11}]_2$
Anthophyllite Magnesium silicate with varying amounts of iron in the lattice	$(Mg,Fe)_7[(OH)Si_4O_{11}]_2$
Tremolite Calcium magnesium silicate	$Ca_2(Mg,Fe)_5[(OH)Si_4O_{11}]_2$
Actinolite Calcium magnesium silicate with varying amounts of iron	$Ca_2(Mg,Fe)_5[(OH)Si_4O_{11}]_2$

Table 1.1: Types of asbestos (Winson, 1975)

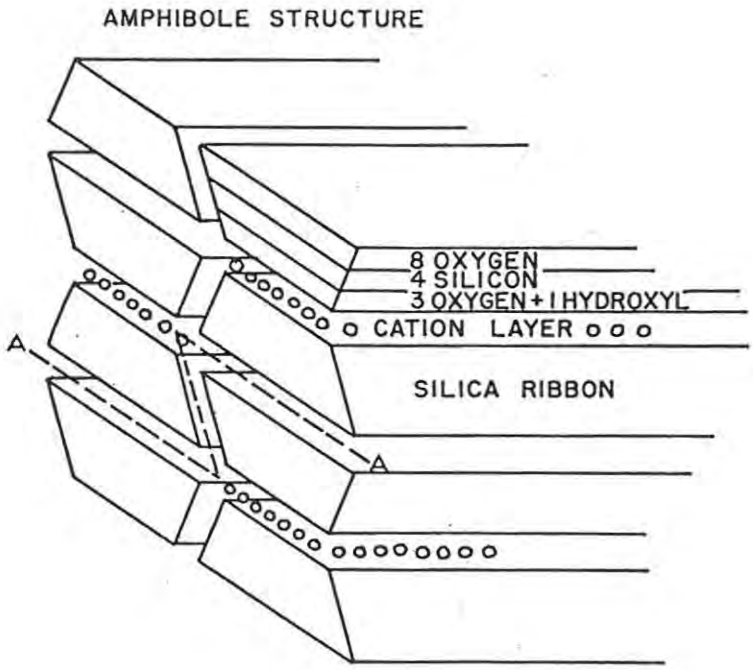


Figure 1.3: The amphibole asbestos crystal structure showing a double silica chain. These form a sandwich of ribbons with a marked cleavage A-A (Speil and Leineweber, 1969).

The actual compositions of the various types of asbestos are different to their theoretical formulae due to various impurities and variations in the chemical composition of different deposits. Table 1.2 illustrates the range of compositions for the most important components in commercial asbestos.

	Chrysotile	Crocidolite	Amosite	Anthophyllite	Tremolite
SiO_2, %	37-44	49-53	49-53	56-58	53-62
MgO, %	39-44	0-3	1-7	28-34	0-30
FeO, %	0-6	13-20	34-44	3-12	1.5-5
Fe_2O_3, %	0.1-5	17-20	–	–	–
Al_2O_3, %	0.2-1.5	–	2-9	0.5-1.5	1-4
H_2O, %	12-15	2.5-4.5	2-5	1-6	0-5
CaO, %	tr-5	–	–	–	0-18
Na_2O, %	–	4.0-6.5	–	–	0-9
CaO + Na_2O, %	–	–	0.5-2.5	–	–

Table 1.2: Approximate chemical analysis of asbestos (Winson, 1975).

Physical and Chemical Properties

The structures of asbestos fibres have been intensively studied by many workers who have used X-ray diffraction patterns as a means of identification and classification. Electron micrographs of the more common types of asbestos are illustrated in Figures 1.4 - 1.8.

Chrysotile asbestos has imperfections within the crystal structure and the inclusion of impurities between fibres and at the ends of the fibres near the wall rock. It is very difficult to remove these impurities by mechanical means, so they are present in the final milled product. Generally they do not have any detrimental effect on the industrial use of asbestos except in electrical applications or some filtration systems, where the amount of impurities has to be limited. Figure 1.4 illustrates the softness and flexibility of chrysotile fibre while Figure 1.5 illustrates a unique variety of mass-fibre, developed in a highly sheared environment.

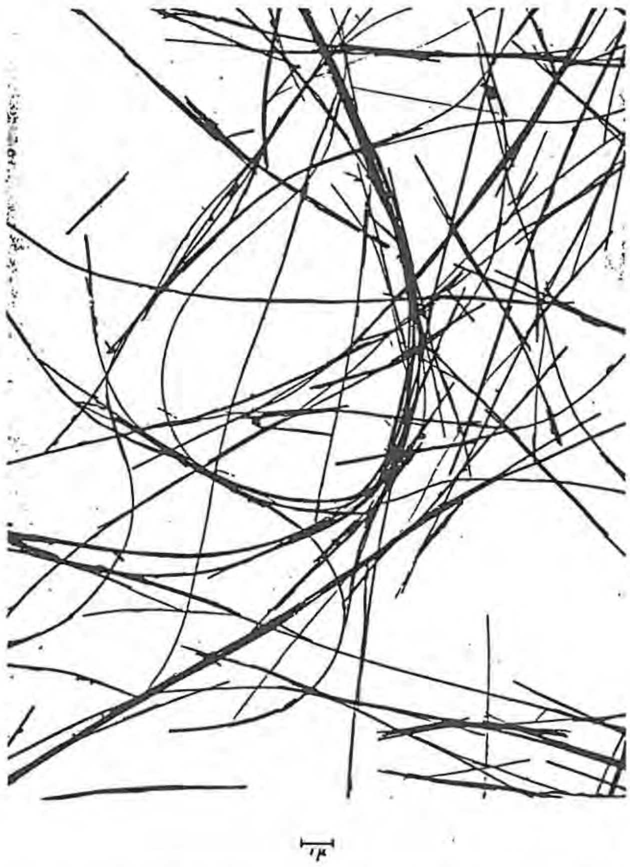


Figure 1.4: Electron micrograph of chrysotile asbestos fibre from Jeffrey mine, Canada, illustrating its softness and flexibility, making it suitable for textile-type products. 8000X. (Speil and Leineweber, 1969).

Figure 1.5: Electron micrograph of Coalinga, California, chrysotile asbestos fibre, from a highly sheared environment. 8000X. (Speil and Leineweber, 1969).

Crocidolite and amosite fibres are generally harsher, more springy and more brittle than chrysotile fibres, making them faster draining and more bulky in various manufacturing uses. The fibres are often comparatively long, ranging up to 15 mm (crocidolite) and 5-30 cm (amosite).

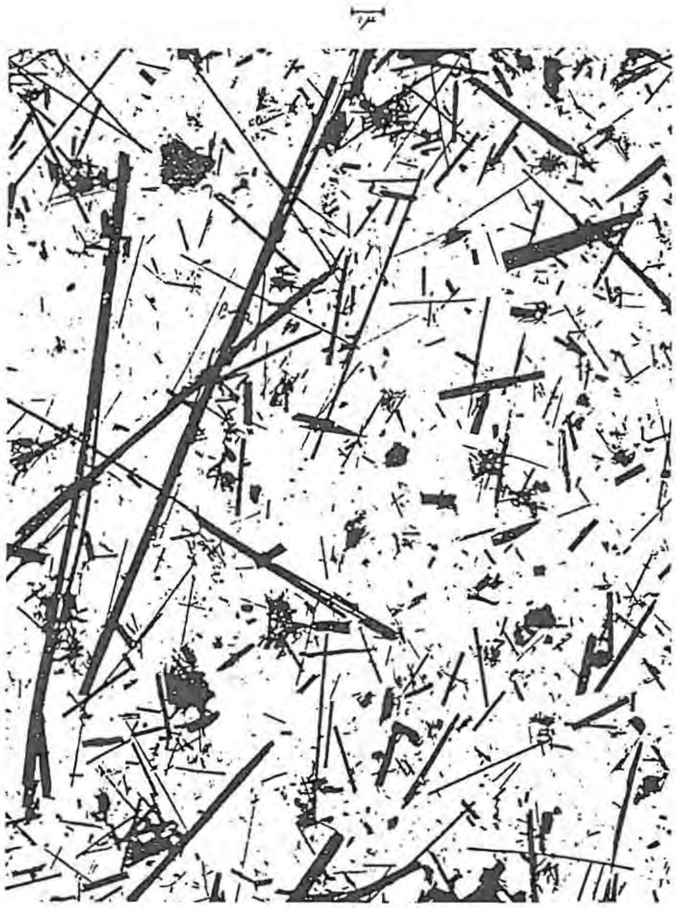


Figure 1.6: Electron micrograph of crocidolite asbestos, illustrating the harsher fibre quality. 8000X. (Speil and Leineweber, 1969)

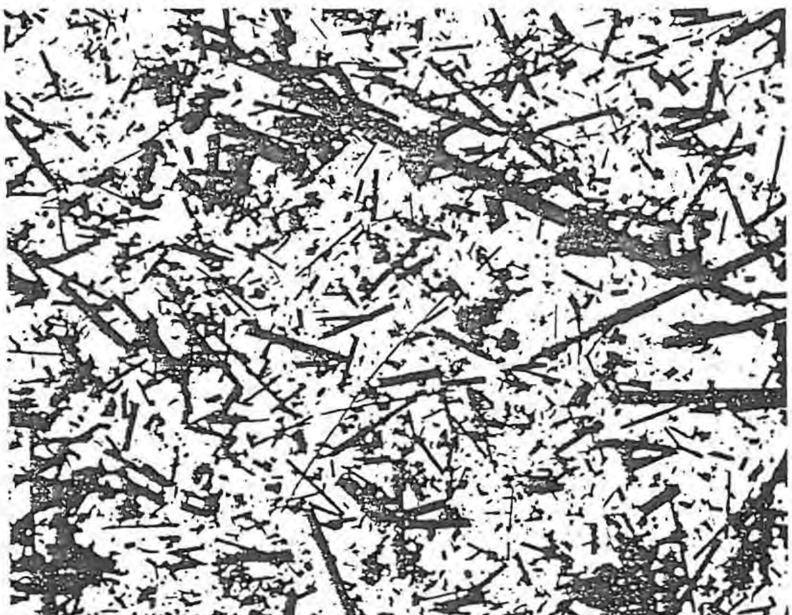


Figure 1.7: Electron micrograph of amosite asbestos fibre, Penge, South Africa. 5000X. (Mann, 1981).

Anthophyllite has a low ignition loss compared to tremolite. It is not known to occur with fibres sufficiently flexible to be spun nor with the tensile strength required to make them of value to the asbestos cement industry (Figure 1.8).

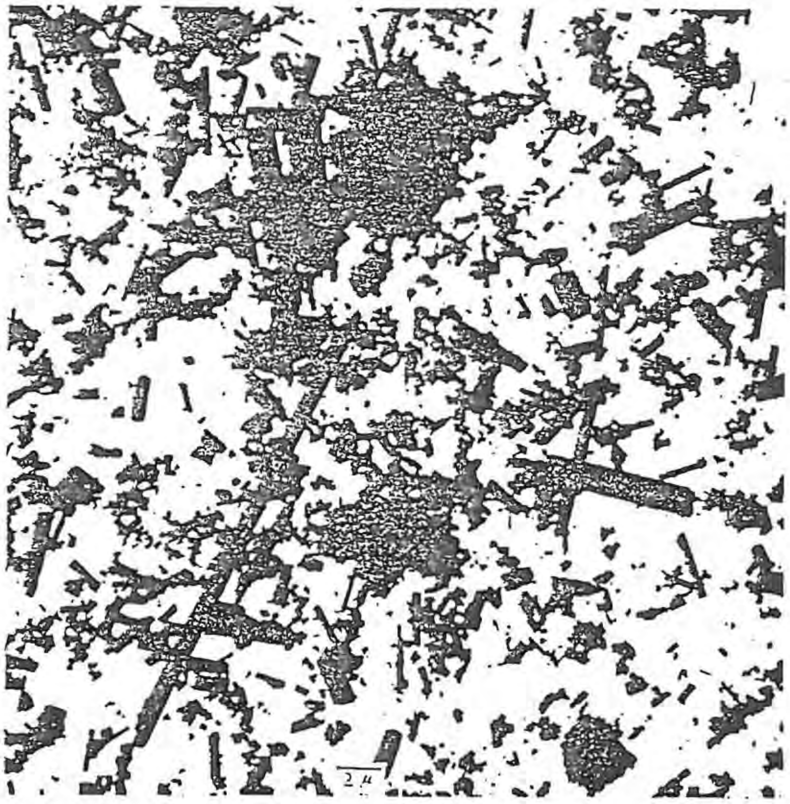


Figure 1.8: Electron micrograph of anthophyllite asbestos fibre, Georgia, U.S.A. 5000X. (Mann, 1981).

A comparison of the general properties of six variaties of asbestos are tabulated in Table 1.3 (Badollet, 1951; Winson, 1975; Mann, 1981). Numerous writers have dealt comprehensively with the physical and chemical properties of asbestos including: Badollet (1948, 1951, 1969); Badollet and Streib (1955); Berry (1971); Bryans and Lincoln (1975); Cossette et al. (1980); Daykin (1971); Gosseye and Hahn-Weinheimer (1971); Griffiths (1980); Martinez (1966); Otouma (1971); Papirer et al. (1980); Parks (1971); Roy et al. (1975); Speil and Leineweber (1969); Winer and Symons (1971).

The fibre length of the milled asbestiform minerals is directly proportional to fibre value, with long fibre commanding high values.

Table 1.3 : Properties of Asbestos Fibre

Property	Actinolite	Amosite	Anthophyllite	Chrysotile	Crocidolite	Tremolite
Structure	Reticulated long prismatic crystals and fibres	Lamellar. Coarse to fine fibrous and asbestiform	Lamellar. Fibrous asbestiform	Usually highly fibrous fibres fine and easily separable	Coarse to fine fibrous	Long. Prismatic and fibrous aggregates
Mineral association	In limestone and in crystalline schists	In banded iron formations	In crystalline schists and gneisses	In altered peridotite and dolomitic limestone adjacent to basic igneous rocks.	In banded iron formations	In Mg limestones as alteration products of highly magnesian rocks. Metamorphic and igneous rocks.
Origin	Results of metamorphism	Regional metamorphism and interference folding.	Metamorphic. Usually from olivine	Alteration and metamorphism of ultrabasic igneous rocks rich in magnesian silicates.	Regional metamorphism and interference folding.	Metamorphic
Veining	Slip or mass fibre	Cross fibre	Slip. Mass fibre unoriented	Cross and slip fibre	Cross fibre	Slip or mass fibre
Essential composition	Ca.Mg.Fe.Silicate water up to 5%	Silicate of Fe and Mg higher iron than anthophyllite; 2-5% water.	Mg silicate with iron with 1-6% water	Hydrosilicate of magnesium with 12-15% water	Silicate of Na and Fe with 2,5 - 4,5% water	Ca and Mg silicate with water up to 5%.
Crystal structure	Long and thin columnar to fibrous	Prismatic. Lamellar to fibrous	Prismatic. Lamellar to fibrous	Fibrous and asbestiform	Fibrous	Long and thin columnar to fibrous
Crystal system	Monoclinic	Monoclinic, or Orthorhombic *	Orthorhombic	Monoclinic (pseudo-orthorhombic?)	Monoclinic	Monoclinic
Colour	Greenish	Ash gray or brown	Grayish white. Brown-gray or green.	White. Gray. Green. Yellowish.	Lavender-blue. Metallic-blue	Gray-white. Greenish. Yellowish. Bluish.
Lustre	Silky	Vitreous. Somewhat pearly	Vitreous to pearly	Silky	Silky to dull	Silky
Hardness	6±	5.5-6.0	5.5-6.0	2.5-4.0	4	5.5
Specific gravity	3,0-3,2	3,1-3,25	2,85-3,1	2,4-2,6	3,2-3,3	2,9-3,2
Cleavage	110 perfect	110 perfect	110 perfect	010 perfect	110 perfect	110 perfect
Optical properties	Biaxial negative extinction inclined	Biaxial and positive extinction parallel	Biaxial positive extinction parallel	Biaxial positive extinction parallel	Biaxial ± extinction inclined	Biaxial negative extinction inclined
Refractive index	1.63± weakly pleochroic	1.64±	1.61±	1.51-1.55	1.7 pleochroic	1.61±
Length	Short to long	Variable 5-30 cm	Short	Short to long	Short to long	Short to long.
Texture	Harsh	Harsh but somewhat pliable	Harsh	Soft to harsh. Also silky	Soft to harsh	Generally harsh. Sometimes soft
Tensile strength, psi	1000 and less	16,000 90,000	4000 and less	80,000 100,000	100,000 300,000	1000 8000
Dehydroxylation temperature °C.	1060-1122	650-735	1010-1020	650-730	360-420	930-988
Filtration properties	Medium	Fast	Medium	Slow	Fast	Medium
Electric charge	Negative	Negative	Negative	Positive	Negative	Negative
Fusion point, °C	1393	1399	1468	1521	1193	1316
Spinnability	Poor	Fair	Poor	Very good	Fair	Poor
Resistance to acids and alkalies	Fair Fair	Fairly good Good	Very good Very good	Poor Fair - very good	Good Very good	Good Very good
Magnetite content	-	0 - 6,5	0	0 - 5,2	3,0 - 5,9	0
Mineral impurities present	Lime, iron	Iron	Iron	Iron, chrome, nickel, lime	Iron	Lime
Flexibility	Brittle and nonflexible	Good; less than chrysotile	Very brittle. Non flexible	Very flexible	Fair to good	Generally brittle; sometimes flexible
Resistance to heat	-	Good. Brittle at high temperature	Very good	Good. Brittle at high temperature	Poor, fuses at high temperature	Fair to good
Relative electrical conductance	-	1.34	0.58	1.82	0.84	-

(Modified from Badollet, 1951; Winson, 1975; Mann, 1981)

* Monoclinic - cummingtonite or grunerite
Orthorhombic - anthophyllite or gedrite

Long fibres can be woven into textile-type fabrics while short fibres are primarily used for reinforcing purposes. Amosite has the longest fibres, followed by crocidolite and chrysotile. Laubscher (1983a) reports 300 mm chrysotile fibres from the New Amianthus mine while Hall (1930) and van Biljon (1959) describe 150 mm chrysotile fibre lengths developed in serpentinized dolomites at the Congo-Vaal mine.

Textures are variable with good quality chrysotile fibres usually soft and silky while the asbestiform amphibole fibres are generally harsher. The fibre quality is due to mineral impurities within the fibre, described by Riordon (1955) and Laurent (1975 b). The latter suggests that the quality of the fibres appears to be primarily related to the residual amounts of iron and aluminium replacing magnesium in octahedral coordination. The magnitude of the magnesium substitution by iron and aluminium is reflected by the $MgO:SiO_2$ ratio which increases with fibre quality, as calcium and aluminium decrease.

Speil and Leineweber (1969) have found that harsh fibres yield fast to medium filtration properties as they have an open and bulky mass. The flexible, soft fibres form stringy, dense masses with slow filtration characteristics. This specific attribute of soft chrysotile is often a serious disadvantage in wet processing techniques employed in the manufacture of asbestos-cement products. Semi-harsh chrysotile fibres or crocidolite can partially replace soft chrysotile to improve filtration. Considerable research has been devoted to correlate harshness with fundamental physical or chemical properties. Badollet and Streib (1955) have patented a technique for increasing the harshness of chrysotile by flash calcining in the range of 500°C to drive off part of the chemically combined water.

The tensile strength of asbestos is of prime importance as it is used primarily as a reinforcing fibre. Crocidolite has the highest tensile strength followed by chrysotile and amosite. Bryans and Lincoln (1975) showed that fibre failure normally occurred by rupture of weak interfibrillar bonds, rather than true tensile failure of fibre. Fibre strength is affected more by crystal imperfections introduced during fibre formation rather than by the atomic arrangement or structure of the fibre.

The dehydroxylation temperatures of the asbestos minerals range between 360°C (crocidolite) and 1122°C (actinolite). The variations in tensile strength and interfibrillar shear strength are affected by heating the fibres. Weight losses for the amphiboles are considerably less than for chrysotile because of much less available hydroxyl ions to be driven off as water. In spite of this, the amphiboles, after heating to about 400°C, will still be more brittle than chrysotile heated to about 600°C. Badollet and Streib (1955) showed that chrysotile retains 32% of its strength even after heating at 650°C.

Amphibole asbestos fibres also decompose at higher temperatures especially when ferrous iron is present, as it causes complex decomposition which is dependent on atmospheric compositional variations. Speil and Leineweber (1969) show that both the dehydroxylation and decomposition temperatures appear to increase with increased MgO content in the different amphibole minerals.

Fiberization is the basic beneficiation method for asbestos fibres and ideally, the fibre bundles should be opened without reducing the fibre length. In practice, the fibres are shortened not only by the severity of the mechanical action but even more by the brittleness or harshness of the fibre. The soft chrysotiles show minimum length disintegration during opening while, for the same mechanical attrition, the semi-harsh and harsh chrysotiles are shortened significantly. Amphiboles are even more susceptible to length attrition by mechanical impact and are usually given their final opening by the ultimate consumer. Mann (1981) reports that structural changes in chrysotile can occur under conditions of intense grinding. This causes the structure to become amorphous due to localized temperature surges within the fibrils which produces dehydroxylation as the tremendous impact energies are absorbed.

Chrysotile develops a positive electric charge in water which enables it to attract or to be attracted to most dispersed materials. Amphibole asbestos develops a negative surface charge which means that fibres disperse and produce an open lattice work in water that has excellent filtration rates and rapid drainage. The latter property is of importance for asbestos cement products.

The magnetite content of asbestos is variable, ranging from 0 to 6,5 per cent. Magnetite often occurs intimately associated with some chrysotile, amosite and crocidolite asbestos, and it may or may not be easily removed. The presence of magnetite does not present a problem in many applications but it does increase the electrical conductivity of asbestos, making it unsuitable for electrical applications. Chrysotile asbestos from serpentinized dolomitic limestones and some amosite fibres are magnetite-free, making them most useful for electrical products.

Other mineral impurities including fragments of host rock, brucite, carbonates, magnesite, awaruite and ferrit-chromite, may be deleterious or beneficial, depending on the type of application.

Resistance to acids ranges from poor to very good. Chrysotile, because of its basic structure, is seriously attacked by strong acids and should not be exposed to them. Most amphibole fibre varieties are more acid resistant but they can exhibit some weight losses when exposed to boiling concentrated acids.

Resistance to alkalies ranges from fair to very good. Chrysotile is resistant to weak alkalies but is attacked by boiling concentrated solutions. Most amphibole asbestiform minerals are also alkali resistant.

World Production of Asbestos

Chrysotile asbestos constitutes about 94 per cent of the current world production of asbestos fibre. Almost the entire amount is derived from deposits whose host rocks are ultramafic in composition (Hall, 1930; Riordon, 1955; van Biljon, 1959; 1964; Laubscher, 1963; 1964; 1968; 1980 a, 1983 a, 1983 b; Winson, 1975; Anhaeusser, 1976; Stewart, 1976; 1978; Petrov and Znamensky, 1978; Butt, 1978; Voigt et al., 1980, 1983; Mann, 1981). A minor amount of chrysotile asbestos production is derived from serpentinized dolomitic limestone (Hall, 1930; van Biljon, 1959; 1964; Shao-Ying et al., 1980; Wen, 1980). Among the other varieties of asbestos, amosite and crocidolite are found in certain metamorphosed ferruginous sedimentary formations and together account for some 5 per cent of world production. Tremolite and anthophyllite make up the remainder of production and are generally found in association with highly metamorphosed ultrabasic rocks. Potassium richterite is an amphibole asbestos found in siliceous dolomitic rocks, but is of minor importance (Wylie and Huggins, 1980).

The major asbestos deposits of the world occur in two principal geological settings, namely a tectonic domain, and a cratonic domain. The tectonic domain coincides with the major orogenic belts : the Urals, the Appalachians and the Rocky Mountains, which contain a major proportion of the world's chrysotile asbestos deposits. The cratonic domain contains chrysotile, crocidolite,amosite and anthophyllite varieties, which includes southern Africa, Brazil, Canada, India and Australia. The major world asbestos producers are tabulated in the Appendix (A1 - A4).

The bulk of the world chrysotile production comes from the U.S.S.R. and Canada, with Zimbabwe and China, then Brazil, South Africa and Italy all producing a large portion (see Appendix, A5). Crocidolite and amosite production is dominated by South Africa. Anthophyllite fibre is produced in the U.S.A., India, Japan, and Yugoslavia with the probable reopening shortly of the Marita mine in Mozambique. Finland was previously the major producer but resources have been depleted. Tremolite is produced in Italy and Turkey but is of minor importance. Comprehensive descriptions of asbestos deposits of the world are contained in Straw (1955), Rowbotham (1970), Winson (1975), Mann (1981), Clarke (1982) and others. The asbestos deposits of the world are illustrated in Figure 1.9.

Russian production comes mainly from the Bazhenovo district of the central Urals, the Dzhetygara area of northwest Kazakhstan, the Kiembay area in the southern Urals and Aktovrak in the Tuva district. The Molodeznoje deposit in the Bam district is of excellent grade and has been evaluated as among the best in the world. The deposit will have to await development until the Baikal-Amur railway is constructed to the deposit. Very rich deposits have been found near Taksimo, adjacent to this railway, near the southern end of Lake Baikal (Industrial Minerals, No. 175, p.131, April 1982).

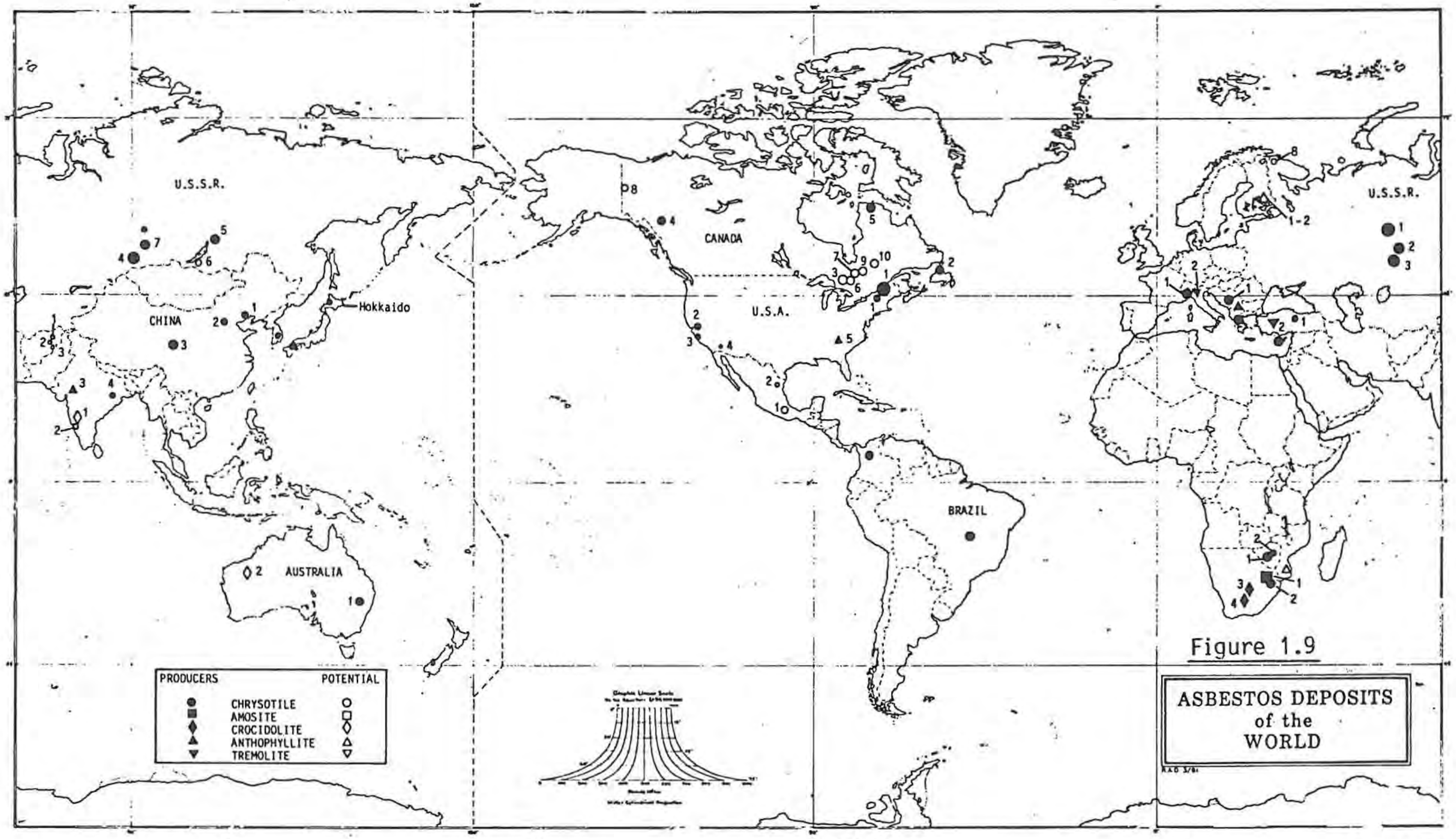


Figure 1.9

ASBESTOS DEPOSITS of the WORLD

CANADA

1. Eastern Townships, Quebec.
2. Advocate, Baie Verte, Newfoundland.
3. Matheson, Ontario.
4. Cassiar, British Columbia.
5. Asbestos Hill, Ungava, Quebec.
6. Bird-Ginn, Cochrane, Ontario.
7. Reeves and Lloyd Lake, Cochrane, Ontario.
8. Clinton Creek, Yukon Territory.
9. Abitibi Deposit, Amos, Quebec.
10. McAdam Deposit, Chibougamau, Quebec.

MEXICO

1. Pegaso, Cuicatlan, Oaxaca State.
2. Cuidad Victoria, Tamaulipas State.

U.S.A.

1. Eden, Vermont
2. Copperopolis, California.
3. Coalinga, San Benito County, California.
4. Gila County, Arizona.
5. Greenmountain, Yancy County, N. Carolina.

COLOMBIA

Las Brisas, Antioquia

BRAZIL

Cana Brava, Uruaca, Goias State

AUSTRALIA

1. Woodsreef, New South Wales.
2. Hamersley Range, Western Australia.

INDIA

1.–2. Bababudan Hills, Chikmagalur district, Mysore State
3. Udaipur-Beawer districts, Rajasthan State.
4. Roro, Bihar State.

CHINA

1. Chin-Chou (Jinzhou), Liaoning Province.
2. Laiyuan, Hopeh (Hebei) Province.
3. Shimien, Szechwan (sichuan) Province.

AFGHANISTAN

1. Bagram Parvan Province.
2. Lowgar, Kabul- Gardez Province.
3. Shodal, Paktia Province.

SOUTH KOREA

Kwangchou and Hongsong, Hongsonggun.

U.S.S.R.

1. Uralasbest, Bazhenovo district, Central Urals.
2. Dzhetygara, Kazakhstan, Southern Urals.
3. Kiembay, Orenburg, Southern Urals.
4. Tuvaasbest, Ak Dovurak, Tuva district.
5. Molodeznoje, Bam district.
6. Taksimo, Buryat Region.
7. Aspagash, Krasnovask.
8. Pechenge.

TURKEY

1. Cavdar, Sivas.
2. Mihalliccik Tatarcik, Eskisehir.

ITALY

1. Balangero, San Vittore, Turin district.
2. Val Malenco, Sondrio district.

ZIMBABWE

1. Shabani-Filabusi districts
2. Mashaba district.

SOUTH AFRICA

1. Penge, N.E. Transvaal
2. Eastern Transvaal
3. Kuruman district
4. Prieska district

SWAZILAND

Havelock, Bulembu.

MOZAMBIQUE

Mavita

JAPAN

Furano-Yamabe, Hokkaido.

FINLAND

1. Paakkila, Tuusniemi Parish
2. Maljasalmi, Kuusjarvi Parish

CYPRUS

Pano Amiandos, Troodos Mountain

GREECE

1. Zidani, Kozani region

YUGOSLAVIA

Bogutoyo, Korlace and Kursumlija, Serbia.

NEW ZEALAND

Pyke, Southern Alps.

The Eastern Townships of Quebec supply the largest portion of Canadian chrysotile asbestos production (Figure 1.10), the fibre developed in serpentinized ophiolite thrust sheets of the northern Appalachians. Cassiar in northern British Columbia, Asbestos Hill in Ungava, the Matheson area of Quebec, and Advocate in Newfoundland contribute the balance of Canadian production.

Almost the entire southern African chrysotile deposits are contained within Archaean ultramafic complexes associated with the ancient greenstone belts on the Kaapvaal (ca 3400 Ma) and Rhodesian (ca 2900-2600 Ma) Cratons, which have been comprehensively reviewed by Anhaeusser (1976a). The Kaapvaal Craton contains the Barberton greenstone belt which has two large chrysotile deposits at Msauli, South Africa, and Havelock, Swaziland. The Rhodesian Craton contains numerous greenstone belts of which the Shabani ultramafic body, the Mashaba Igneous Complex, Filabusi, Gwanda and Lower Gwanda greenstone belts are of economic importance.

China is the world's fourth largest producer of chrysotile asbestos with 250,000 tons of fibre produced in 1980. Wen (1980) describes deposits developed within serpentinized ultramafic and dolomitic rocks, but little is known about the geology of the deposits (see Appendix, A5).

Brazil is the world's fifth largest producer of chrysotile asbestos. The Cana Brava asbestos deposit is located some 200 km north of Brasilia and 100 km northeast of Uruacâ in the State of Goiás. Little is known about the deposit except that it occurs in a large ultrabasic body which intrudes gneisses of the Brazilian Precambrian Shield. The ore is apparently a good quality cross fibre of medium length which occurs in two separate zones 600 m long and roughly 60 m wide. The bulk of this fibre is utilized by local Brazilian manufacturers (Mann, 1981).

Minor chrysotile asbestos deposits occur in serpentinized dolomitic rocks associated with intrusive dykes and sills which thermally alter the host rock. The Malmani Dolomite Subgroup of the Transvaal Supergroup (ca 2000 Ma) contains chrysotile asbestos deposits located in the eastern Transvaal of South Africa. Bushveld Igneous Complex-age sills (ca 1950 Ma) intruded the dolomitic rocks and metamorphosed a portion of

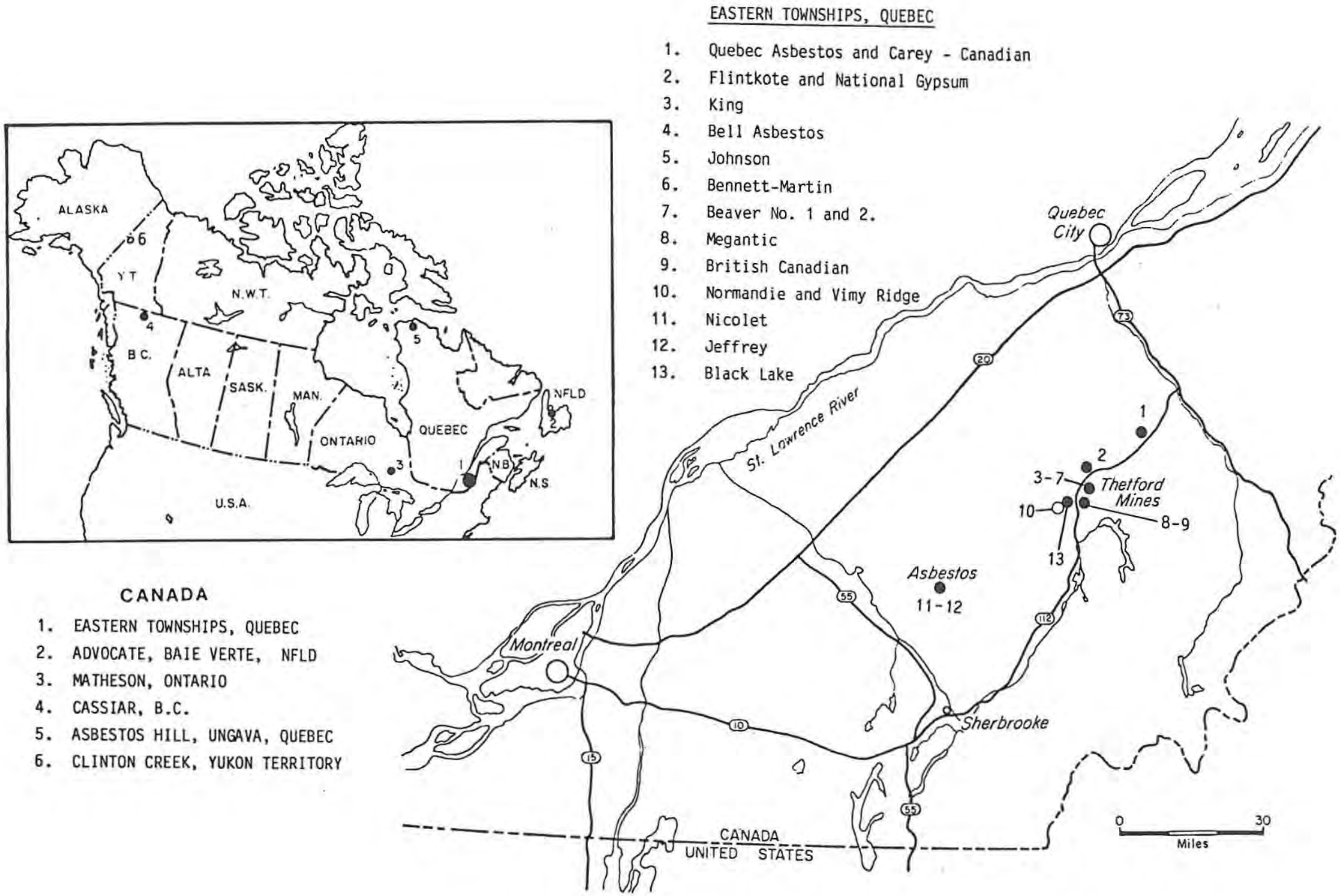


Figure 1.10: Asbestos mining areas in Canada. At right, the Eastern Townships of Quebec. (Modified from Winson, 1975; Mann, 1981)

the host rock above the upper chilled contacts. Chrysotile fibre is developed in these alteration zones where interbedded chert occurs (Hall, 1930; van Biljon, 1959; 1964). Other occurrences of dolomite-hosted chrysotile asbestos are in the U.S.S.R. at Aspargash, Krasnovask area; the U.S.A. in Arizona, and northern China.

South Africa contains almost the entire economic deposits of crocidolite and amosite amphibole asbestos. These deposits occur in Precambrian banded iron formations in the northeastern Transvaal and northern Cape Province. Comprehensive descriptions are found in Hall (1930), du Toit (1945), Vermaas (1952), Keep (1961), Cilliers (1964), Cilliers et al. (1961), Cilliers and Genis (1964), Genis (1964), Hanekom (1966), Fockema (1967), Welch (1969), Dreyer (1974), Button (1976), Dreyer and Robinson (1978), Beukes (1978).

Widespread occurrences of crocidolite and amosite are known to occur in the Bababudan Hills north of Chikmagalur in Mysore State, India (Winson, 1975; Mann, 1981). Both varieties of fibre occur in an assemblage of banded ironstones and shales similar to those of north-eastern Transvaal but the amosite in particular is noticeably shorter. However, one area of amosite has been intensively investigated for possible production.

Deposits of crocidolite have been found in the Hamersley range of Western Australia in similar banded iron formations to those in South Africa. These deposits have been described by Miles (1942), Trueman (1963), Finucane (1965), Trendall and Blockley (1970) and Blockley (1976).

The Russian amphibole asbestos deposits of Kazakhstan have been briefly described by Beiseyev (1980), but they are of minor importance. The genesis and chemistry of these fibrous amphiboles have been studied by Grigor'eva et al. (1971), Makarova et al. (1971) and Korytkova et al. (1975). Wylie and Huggins (1980) have described a potassium winchite-richterite amphibole asbestos from the Allamoore talc district of Texas. The origin of the asbestos is attributed to low temperature metasomatism of a siliceous dolomite. The asbestos is light grey, with individual fibres commonly longer than five centimetres. The fibres are silky, have good tensile strength and are sufficiently flexible to be easily woven. This asbestos possesses all the characteristics of the commercial asbestos fibres and has a low Fe content which is of particular value to the electrical industry.

The age of chrysotile asbestos deposits varies greatly from Precambrian in South Africa and Swaziland (ca 3400 Ma) and Zimbabwe (ca 2900-2600 Ma) to Upper Jurassic in California. The Ontario, Ungava and Brazilian deposits are all Precambrian, while those of the Eastern Townships, Vermont and Newfoundland are all ascribed at Mid-Paleozoic age, associated with early folding in the Appalachian mountain belt. The deposits of western Canada are connected with mountain building in the Late Paleozoic while the Russian deposits vary from Early Paleozoic to Late Paleozoic or Triassic in age.

The dolomitic-hosted chrysotile asbestos of South Africa is given an age of ca 1950 Ma, the age of Bushveld Igneous Complex sills.

The crocidolite and amosite amphibole asbestos deposits are developed within Early Proterozoic banded iron formations of the Transvaal Supergroup (ca 2300-2100 Ma). The amosite fibre is thought by some writers to have formed within the Bushveld Igneous Complex metamorphic aureole which intruded these host rocks at ca 2000 Ma.

GEOLOGY OF CHRYSOTILE ASBESTOS

The world's largest producing chrysotile asbestos mines occur in serpentinized ultramafic portions of ophiolite suites in the U.S.S.R. and Canada. Other major deposits occur in serpentinized Precambrian ultramafic complexes in Zimbabwe, South Africa and Canada. Minor magnetite-free chrysotile asbestos occurs in serpentinized dolomitic limestones in South Africa, U.S.A., U.S.S.R. and China.

The process of chrysotile asbestos vein development is a part of the serpentinization process, but not all serpentinization produces chrysotile asbestos deposits. An understanding of the formation of chrysotile asbestos requires an understanding of the various types of serpentinization (Wicks and Whittaker, 1977).

Structural control of the host rock is of primary importance for fibre genesis. Faulting, fracturing, folding and shearing localizes asbestos deposits while tensional stress conditions within the host rocks are essential to enable fibre to crystallize from serpentinous solutions. These solutions are generated within the host rock by hydrothermal fluids and pervade the rock through suitable fractured channelways where crystallization occurs under favourable temperature and stress conditions. Field evidence indicates that fibre occurs as stress-controlled dilation seams, as a recrystallization product of serpentine minerals and as a result of the serpentinization of olivine.

A specific combination of faulting, shearing, folding, serpentinization, the presence of serpentinous solutions, and metamorphism of the ultramafic host rock is required for the formation of chrysotile asbestos. Economic deposits are found in those areas where all the controlling factors have been satisfied. Thus, not all serpentinized ultramafic and dolomitic limestone rocks contain chrysotile asbestos deposits.

Host Rocks

These comprise ultramafic ophiolite suites, Precambrain layered ultramafic complexes and dolomitic limestones. All of these rocks must be serpentinized before they can become potential fibre-bearing hosts.

Ultramafic ophiolite suites

The major chrysotile asbestos deposits of the U.S.S.R., Canada and China, and occurrences in Italy, Yugoslavia, Cyprus, Greece, Turkey, Afghanistan, Colombia, Mexico, eastern and western U.S.A., western Canada, Japan, Australia and New Zealand, are contained within tectonic domains coinciding with major orogenic belts (Figure 2.1).

The major portion of the Canadian chrysotile asbestos is derived from Paleozoic alpine- type ophiolite suites of peridotite and pyroxenite. These suites are intrusive into, and folded with, the Cambrian to Devonian

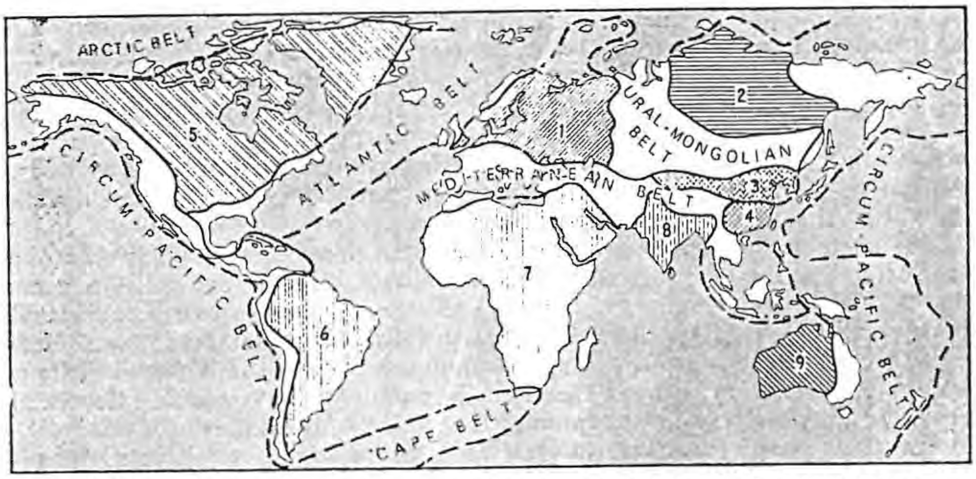


Fig. 2.1 : Ancient platforms and geosynclinal folded belts (after Muratov, 1966): 1 - the East European platform; 2 - Siberian; 3 - Sino-Korean; 4 - South China; 5 - North American; 6 - South American (Brazilian); 7 - African; 8 - Indian; 9 - Australian.

(Beloussov, 1980)

eugeosynclinal sediments of the Appalachian belt in the Thetford district of the Eastern Townships of Quebec (Figure 2.2) (Cooke, 1936; 1937; Riordon, 1957 a; Laurent, 1975 a; Laurent, 1975 a; 1975 b; Anhaeusser, 1976 a).

The three principal asbestos producing regions of the U.S.S.R. are located in the Bazhenovo, Dzhetygara and Kiembay districts of the central and southern Urals. These deposits occur in late Precambrian to Paleozoic orogenic terrain, related to geosynclinal evolution, between the Russian and West Siberian Platforms (Figure 2.3, (7)). The other large Russian deposits of Aktovrak and Sayansky (Figure 2.3, (13)), Taksimo and Molodeznoje (Figure 2.3, (14)), are also associated with the orogenic stage of geosynclinal evolution between the Siberian and Sino-Korean Platforms (Bilibin, 1968; Petrov and Znamensky, 1978; Vedernikov, 1980; Kuznetsova, 1980).

The pricipal chrysotile asbestos deposits in China are located on the geosynclinal margins of the ancient platforms of Sino-Korea and South China (Figure 2.1). The northern Chinese deposits are related to the southwestward extension of the Cimmerian- Hercynian geosynclinal cycles of the Transbaikal- Maritime region of the far western U.S.S.R.

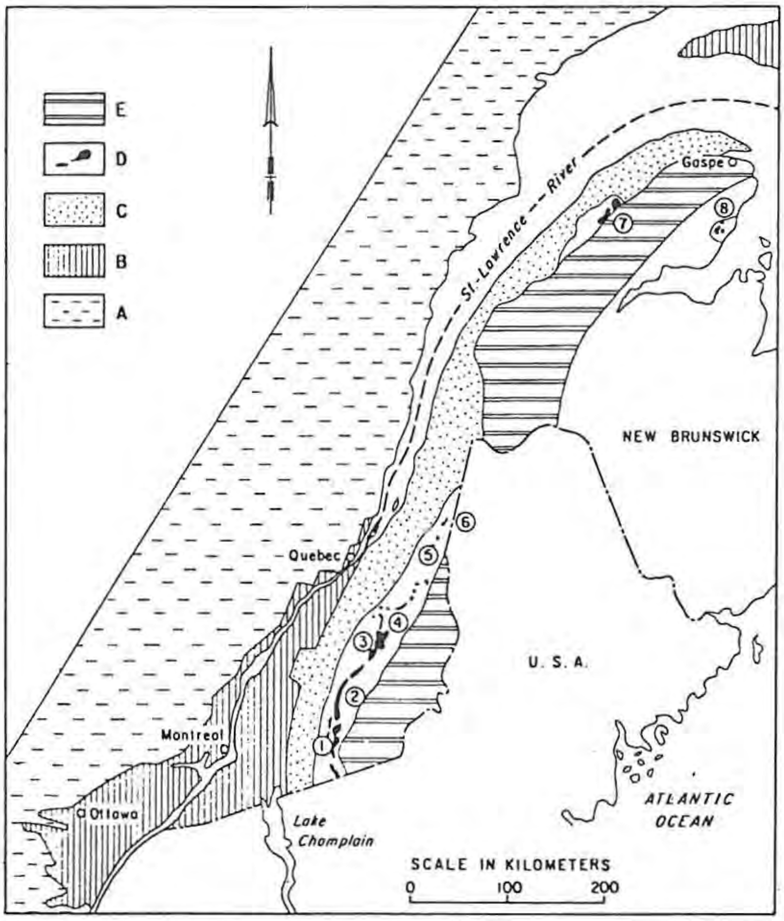


Fig. 2.2: Map of the Appalachians of southwestern Quebec showing the main structural zones and the major ophiolite localities: (A) Precambrian crystalline basement, (B) sedimentary cover of the St. Lawrence Platform, (C) outer zone or external flysch trough, (D) inner zone or Notre Dame Trough, (E) Siluro-Devonian belt of the Gaspé - Connecticut Valley Synclinorium. (1) Orford, (2) Asbestos, (3) Thetford Mines, (4) East Broughton, (5) St. Fabien, (6) St. Omer, (7) Mont Albert, (8) Riviere Port Daniel. (Laurent, 1975 a).

(Figure 2.3, (6)) and are similar to the Russian deposits. The central and southern deposits are associated with the geosynclinal terrain of the Mediterranean belt (Figure 2.1). There are eight large and medium sized deposits containing more than 40 million tons of fibre developed in serpentinized ultramafic rocks, with fibre content ranging between 2,5 - 5%. Slip fibre occurs at Sichuan and Xingkang mines, while cross fibre is found at Mangai mine (Wen, 1980).

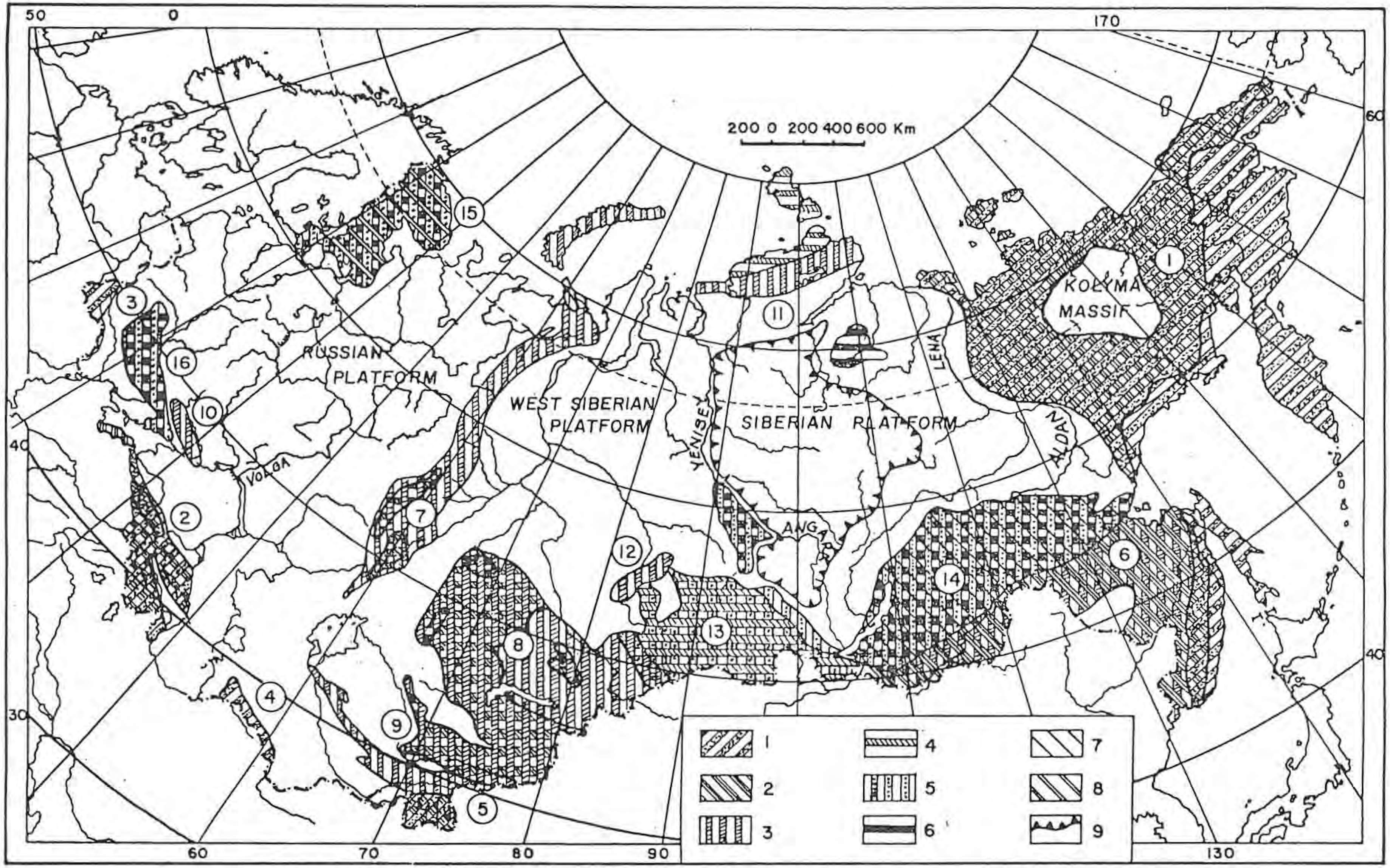


Fig. 2.3: MAP OF METALLOGENIC REGIONS OF THE SOVIET UNION (After V.I. Smirnov)*

LEGEND

Distribution of metallogenic epochs of geosynclinal cycles	Ore-bearing provinces (figures in circles)
1. Alpine (Mesozoic-Cenozoic)**) 3. Hercynian (Upper Paleozoic) 5. Proterozoic 2. Kimmerian (Triassic-Jurassic). 4. Caledonian (Lower Paleozoic). 6. Archean	Alpine. 1. Far Northeast. 2. Caucasus. 3. Carpathians. 4. Kopet Dag. 5. Pamirs. Kimmerian. 6. Transbaikal-Maritime Region. 7. Urals. 8. Kazakhstan. 9. Turkestan. 10. Donets Basin. 11. Taimyr. 12. Tom-Kolyvan Zone.
*) Essays of Metallogeny, Moscow, 1963. **) Translator's notes—in parentheses.	Caledonian. 13. Altai-Sayan Zone. Proterozoic. 14. Southern part of Siberian Platform. 15. Baltic Shield. 16. Ukrainian Shield.

(Bilibin, 1968)

The Canadian chrysotile asbestos deposits of Quebec's Eastern Townships occur intermittently within the serpentinized ultramafic rocks of an ophiolite suite which arcs northeastwards into the Gaspe Peninsular and southwards into the Appalachian Mountain belt of Vermont (Figure 2.2). The ophiolites are thrust sheets with complex faulting, thrusting and folding. This thrust zone forms a 250 km belt called the Serpentine Tectonic Belt which locally dismembers and fragments the ophiolite sequences. Most of the major asbestos occurrences are located along a 90 km length from East Broughton southwards to Orford near the U.S.A. border. The ophiolite sequence comprises peridotites (harzburgites) with well developed tectonic fabric, overlain by cumulate textured dunite, pyroxenite, gabbroic and dioritic rocks. The peridotites and dunites are usually serpentinized with associated granitic, rodingitic and talc-carbonate rocks. The stratified sheets have a simple, regularly-layered structure with no well developed sheeted-dyke complex. A relatively thick ultramafic-cumulate occurs at the base with a thicker lower unit of Alpine peridotite. Laurent (1975a) suggests that these ophiolites represent fragments of an oceanic crust formed on a rapidly spreading ridge and obducted onto the continental margin contemporaneously with the development of a subduction zone. Laurent (1975b) concluded that the peridotite was originally hydrated and serpentinized after cooling to a temperature lower than 485°C and some ophiolite fragments later obducted onto the Appalachian continental margin.

The ultrabasic rocks concordantly intrude Cambrian to Ordovician stratified metasedimentary and metavolcanic host rocks. The emplacement of the ultramafic intrusives has been dated at 495 Ma (Lower Ordovician) and they have been intruded by Devonian-age granitic bodies (Laurent, 1975a ; Douglas, 1976). The ophiolite sequence is thrust to the north-west over the metasedimentary rocks of the Caldwell Group, forming a major fault zone. Near the end of these tectonic movements, asbestos veins started forming in dilation fractures throughout the peridotite. The chrysotile fibres formed at temperatures lower than 400°C through the action of oxygen-rich waters (Laurent, 1975b). All the asbestos deposits of southern Quebec occur close to this fault zone. Wicks (1980) describes the importance of this fault zone and associated faults which localizes fibre development in the Jeffrey, Nicolet, Vimy, Normandie and

Penhale mines. The shear zones disrupting the ultramafic sequences do not contain economic asbestos fibre; however, the serpentinized peridotite occurring between the shear zones is intensely shattered and these fractures provide the site for the development of a stockwork of chrysotile asbestos veins.

The simple, regularly layered structure of the southern Quebec ophiolites is illustrated by the asbestos ophiolite at Jeffrey mine (Figure 2.4).

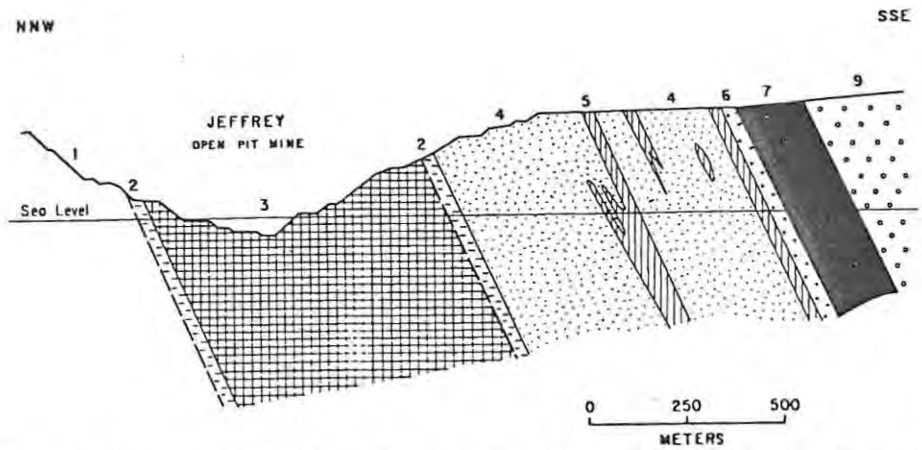


Fig. 2.4: Cross section through the Asbestos Ophiolite at Jeffrey Mine, Johns-Manville Co. Ltd., from Association des Mines d'Amiante du Québec (1972): (1) Cambrian Caldwell Group (country rock), (2) serpentinite, (3) Alpine peridotite (asbestos-bearing harzburgite), (4) dunite, (5) pyroxenite, (6) gabbro, (7) volcanics and volcanic breccias, (9) Early Ordovician St. Daniel Formation (mélange). (Laurent, 1975a)

A serpentinite zone is developed at the contact between the base of the ophiolite complex and the underlying Cambrian country rocks. A second serpentinite, the main shear zone, is developed between the asbestos rich peridotites and the cumulate ultramafic rocks. The peridotite below the second serpentinite comprise extensively serpentinized harzburgites with a metamorphic fabric and veins of cross-fibre chrysotile asbestos. The ultramafics above consist of granular cumulates pervasively serpentinized with cumulate olivine, chromite and diopside. Laurent (1975a) emphasises the economic importance of identifying this second serpentinite horizon. The richest asbestos fibre deposits in the peridotites of the Serpentine Zone are located below this horizon and the main chromite deposits immediately above it. Later CO_2-bearing low temperature meteoric waters partly altered the peridotite to talc and carbonates (Laurent 1975b) and locally affected the chrysotile fibre, creating irregular economic orebodies within the host rock.

The major U.S.S.R. chrysotile asbestos deposits are associated with tectonic geosynclinal domains. Vedernikov (1980) analysed the distribution of large Russian chrysotile deposits and found that the degree of completion of geosynclinal evolution defines the scale of the asbestos deposit and not the age of the fold system. The three most important chrysotile producing areas are associated with Caledonian (lower Paleozoic) folding of the Urals between the Russian and West Siberian Platforms (Figure 2.3). Wenner and Taylor (1974) confirmed that the strongly serpentinized ultramafics from the asbestos deposits of the Urals appear to be typical of alpine serpentinites. Vedernikov (1980) identified three fibre subtypes occurring within these tectonic domains: a) Bazhenovsky subtype - stockwork veins of cross- fibre within dunite-harzburgite host rocks, the fibre zones controlled by major faults; b) Karachayevsky subtype - slip fibre in deformed and sheared serpentinized ultramafics; c) Laba subtype - ribbon fibre, stockwork veins, slip and mass fibre associated with fault zones.

The large chrysotile deposits are located either in the vicinity of major deep faults, in ultrabasics confined to the intermediate geosynclinal formations or in deep eugeosynclinal regions where thick volcanic-sedimentary sequences are developed. Development of chrysotile fibre deposits is determined by the tectonic position and deformation of the dunite-harzburgite ultramafic host rock localized in eugeosynclinal areas and not only by the composition of the host rock. Bilibin (1968) confirmed that the initial stages of geosynclinal evolution produce the essential ultramafic host rocks and tectonism required for chrysotile asbestos fibre formation. Chrysotile asbestos is developed mainly within the Caledonian geosynclinal cycle and there are no known deposits developed in the Mesozoic or Tertiary cycles.

The large chrysotile deposits of Aktovrak and Sayansky are located within the Caledonian geosynclinal cycle of the Altai-Sayan zone occurring between the Siberian and Sino-Korean Platforms (Figures 2.1; 2.3, (13)). These deposits are associated with a belt of serpentinized ultramafic rocks of the Salair complex which forms part of the Lower Hercynian of the eastern Altai-Sayan Province. The ultrabasic intrusives occur intermittently in belts which extend along major faults (Mann, 1981). Chrysotile fibre deposits of excellent grade are located at Taksimo and Molodeznoje within the Proterozoic geosynclinal cycles of the southern margin of the Siberian Platform (Figure 2.3, (14)).

Precambrian ultramafic complexes

The major chrysotile asbestos deposits of Zimbabwe, Brazil, South Africa and Canada, and occurrences in Swaziland and India, are located within Precambrian cratonic domains. The fibre is developed within serpentinized ultramafic complexes occurring either as differentiated sill- like bodies in greenstone belts or as later differentiated intrusives. Anhaeusser (1976a) groups the ultramafic bodies into three varieties. These, in order of decreasing age, are: (1) the layered complexes associated with basaltic and peridotitic komatiite extrusives and forming the basal ultramafic- mafic unit of southern African greenstone belts; (2) layered ultramafic bodies associated with the intermediate to acid volcanic rocks that constitute part of the mafic-felsic unit of greenstone belts; and (3) ultramafic intrusive bodies that postdate the greenstone belts but which are still affected by Archaean tectonic disturbances that arise from the emplacement of granites.

All the principal asbestos- bearing complexes show magmatic segregation into layered, often cyclically repetitive, differentiation sequences. Where fractional crystallization of the ultramafic magma has been most efficient, many layers at, or near, the base of the complexes comprise monomineralic dunite and Mg-rich orthopyroxenites. Although chrysotile asbestos may commonly be encountered in all serpentinized ultramafic rock types, optimum development of economically exploitable fibre generally occurs in dunites, peridotites or harzburgites.

Faulting, fracturing and folding control the localization of asbestos development in the serpentinized ultramafic rocks. Economic deposits are found in those areas where all the controlling factors of suitable host rock, serpentinization of olivine, the presence of solutions and structural control have been satisfied.

Comprehensive accounts of southern African chrysotile asbestos mineralization appear in Hall (1930), van Biljon (1959, 1964), Laubscher (1963, 1964, 1968, 1983a, 1983b), Anhaeusser (1976a), Menell et al. (1981), Barton and Eaton (1980), Barton (in press), Mackenzie (1965), Voigt et al. (1980) and Voigt et al. (1983).

The Kaapvaal and Rhodesian Cratons comprise a great variety of volcanic, sedimentary and granitic elements. Numerous exposed remnants of the Archaean greenstone belts are scattered within the expanse of granitic rocks within these cratons (Figure 2.5). Much of the southern African Archaean is covered by younger formations which obscure about 70% of the cratonic crustal area. Both of these cratons are bounded by high grade polymetamorphic mobile belts which are considered to represent reworked Archaean cratonic material with, or without, infolded, younger supracrustal rocks. The two greenstone terrains are separated by the Limpopo mobile belt, they are different in age and have undergone different tectonism resulting in very different preservation potential.

Condie (1981) observes that, although the oldest known greenstone belts are ca 3500-3800 Ma in age (Barberton and the older greenstone belts in Zimbabwe), most greenstone belts appear to have formed between 2600-2700 Ma (majority of the greenstone belts within the Rhodesian Craton). Both granite- greenstone terranes appear to have a similar origin at Ca 3500 Ma, after which the Limpopo mobile belt separated the two cratons. The younger greenstones developed within the Rhodesian Craton have calc-alkaline volcanism associated with them suggesting that an incipient subduction zone was developed at this time. Structural studies clearly show that the early stages of deformation were characterized by imbrication and overthrusting of nappes directed in a northeasterly direction. The greenstone belts developed a synclinal habit in response to horizontal compressive forces

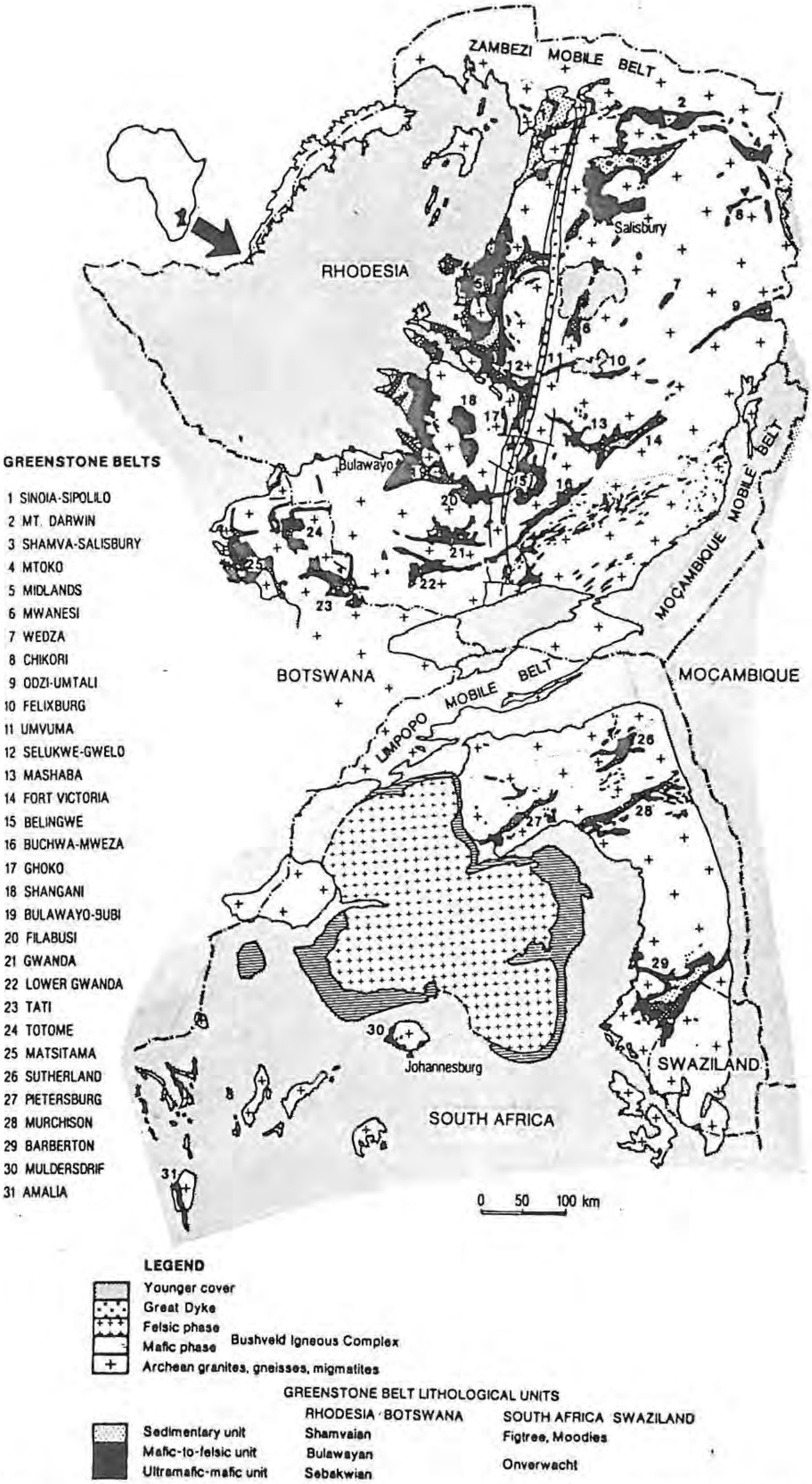


Fig. 2.5: Map illustrating the exposed Archean granite-greenstone terrain of the Rhodesian and Kaapvaal Cratons, southern Africa. (Anhaeusser, 1974)

(Condie, 1981). Preservation of the greenstone belts is far greater within the Rhodesian Craton than within the Kaapvaal Craton due to their difference in ages. Horizontal tectonism was operative in the former craton at ca 2700 Ma while vertical tectonism occurred in the latter craton at about the same time, which also affected this preservation potential.

Ideally Archaean greenstone belts commence with an ultramafic-mafic basal unit, then followed upwards into mafic, intermediate and felsic volcanic rocks, and terminated by a variety of sedimentary assemblages (Anhaeusser, 1974). Most greenstone belts, however, only display parts of the idealized model, being aborted at varying stages, usually by a variety of granitic intrusive rocks. The ultramafic-mafic basal unit is a favourable host rock to chrysotile asbestos development in southern Africa. Fig. 2.6 illustrates the widespread distribution of this fibre variety which is developed in the serpentinized basal ultramafic rocks. Areas of particular importance are the Belingwe, Filabusi, Gwanda, and Lower Gwanda belts in Zimbabwe, and the Tati belt in Botswana within the Rhodesian Craton, and the Barberton remnant within the Kaapvaal Craton. The chrysotile asbestos is not confined to these basal ultramafic rocks but also occurs in sill-like ultramafic intrusives developed less frequently higher in the idealised greenstone assemblage, in the mafic-felsic rocks, at Havelock and Msauli within the Kaapvaal Craton. Economic deposits of chrysotile asbestos also occur in differentiated ultramafic complexes in the Mashaba Igneous Complex and Shabani ultramafic body within the Rhodesian Craton, considered by Wilson (1968) to be younger than the greenstone belts but older than the latest intrusive granitic events in the area.

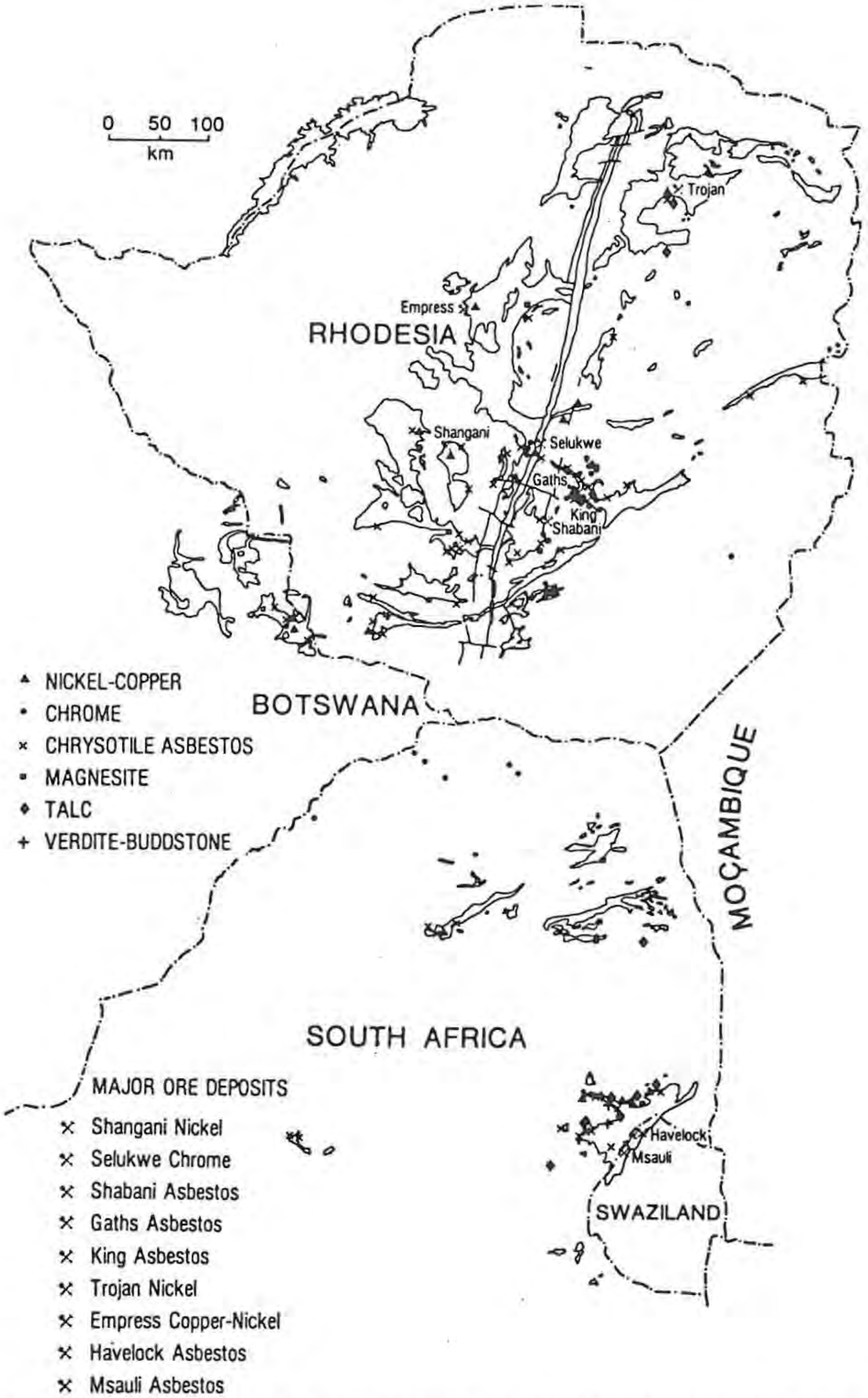


Fig. 2.6 : Map showing the distribution of nickel-copper, chrome, chrysotile asbestos, talc, verdite-buddstone, and magnesite in the Archean greenstone belts of southern Africa. (Anhaeusser, 1974)

The Kaapvaal Craton greenstones are of ca 3400 Ma age and comprise four main remnants : The Barberton, Murchison, Pietersburg and Southerland belts, located within the eastern and northeastern Transvaal. These greenstones are collectively referred to as remnants of the Swaziland Supergroup, which is particularly well developed in the Barberton Mountain Land (Figure 2.7). The greenstone belts are elongated ENE-WSW, parallel to the structural trend of the Limpopo mobile belt. Economic chrysotile asbestos deposits are developed within ultramafic rocks of the Barberton greenstone belt although this fibre variety is also found within the Pietersburg and Muldersdrif belts.

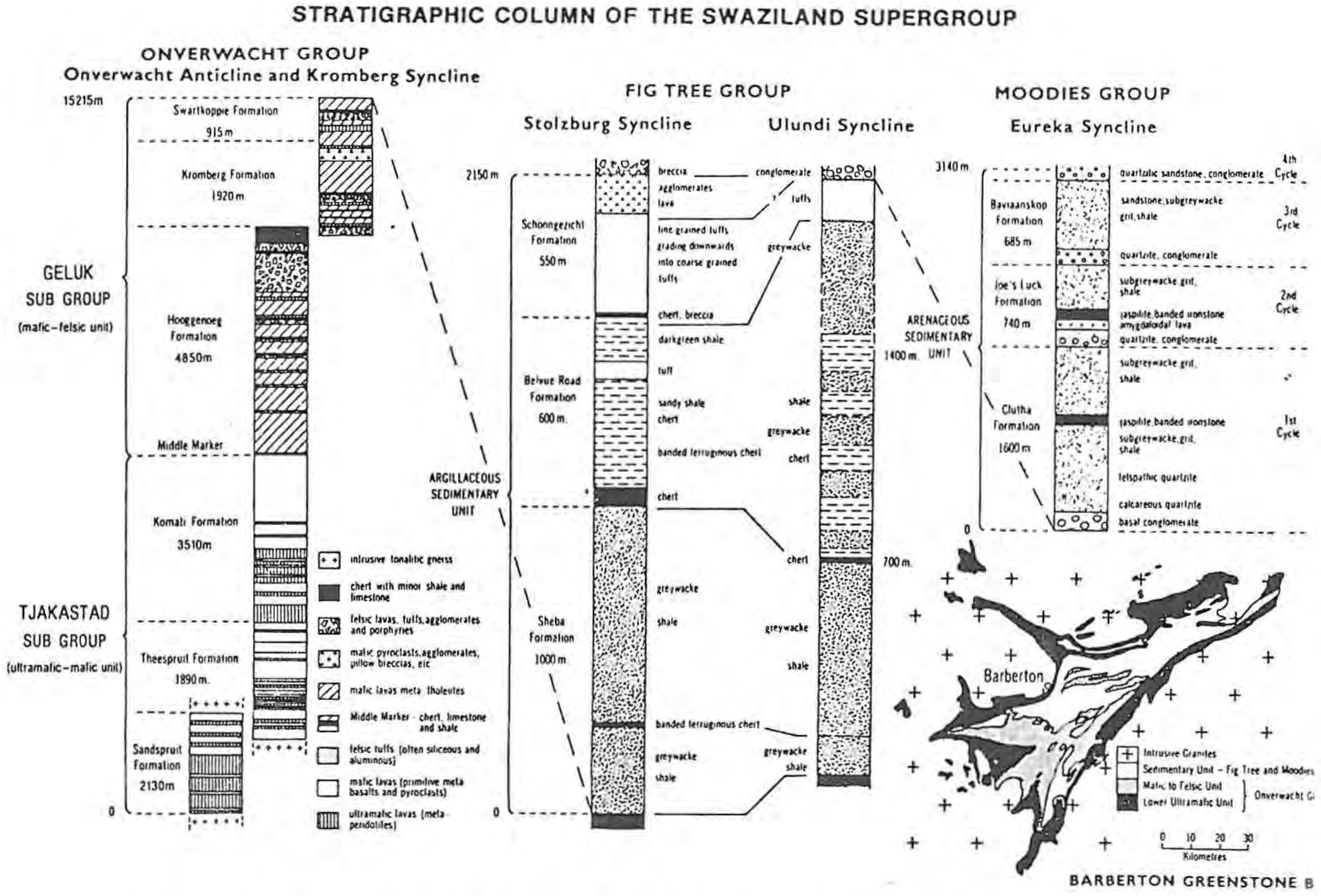
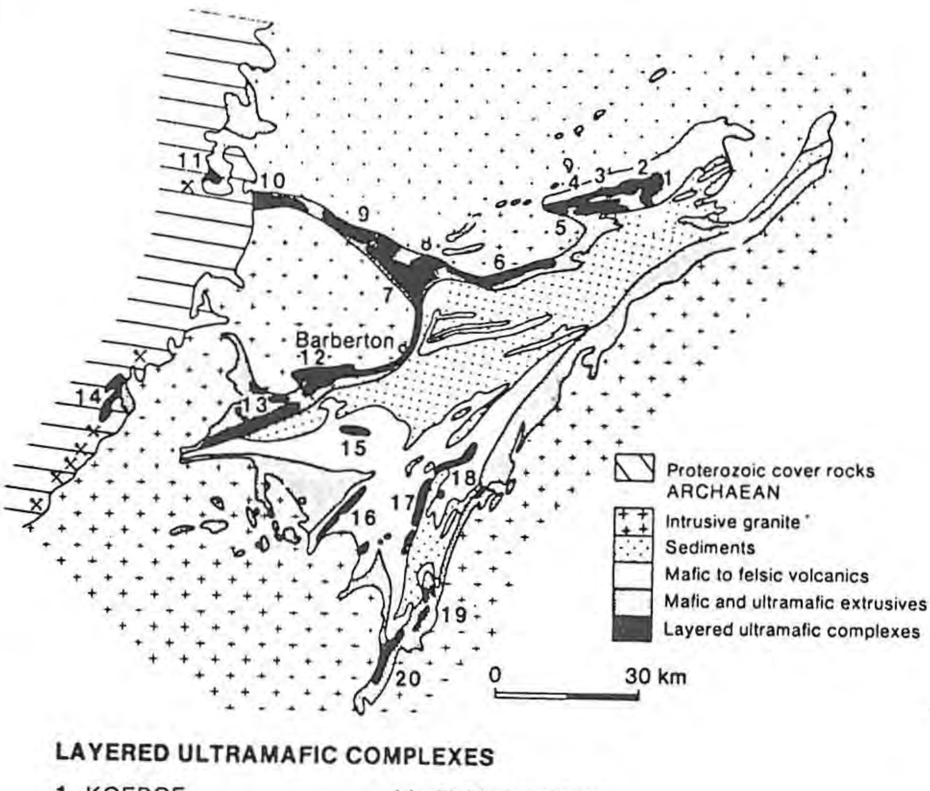


Fig. 2.7: Stratigraphic column of the Swaziland succession in the Barberton Mountain Land, South Africa. The distribution of the Lower Ultramafic Unit, the Mafic-to-Felsic Unit, and the Sedimentary Unit is shown in the inset general geological map of the Barberton greenstone belt. (Anhaeusser, 1975)

The Barberton greenstone belt stratigraphic succession is composed of a volcanic assemblage, the Onverwacht Group, developed at the base of the sequence comprising six formations separated into a Lower Ultramafic Unit and an upper Mafic-to-Felsic Unit by a persistent sedimentary horizon, the Middle Marker. The Lower Ultramafic Unit contains an abundance of high magnesia ultramafic to mafic volcanics, termed komatiites. Numerous layered differentiated ultramafic pods and sills are developed which are particularly favourable host rocks to chrysotile asbestos fibre development. There is widespread distribution of this mineral, coinciding mainly with areas containing abundant serpentinized ultramafic rock. Areas of particular importance are illustrated in Figure 2.8. The Mafic-to-Felsic Unit comprises cyclically alternating



LAYERED ULTRAMAFIC COMPLEXES

1 KOEDOE	11 ELANDSHOEK
2 MAGNESITE	12 HILVERSUM
3 CENTRAL-CANAL	13 STOLZBURG
4 SHIP HILL	14 KALKKLOOF
5 BUDD	15 GRANVILLE GROVE
6 SUGDEN	16 ROSENTUIN
7 HANDSUP	17 MSAULI
8 MUNDT'S CONCESSION	18 HAVELOCK
9 HILLSIDE	19 FORBES REEF
10 KAAPSEHOOP	20 MOTJANE

× Chrysotile Asbestos Deposits in Dolomites of the Transvaal Supergroup

Fig. 2.8 : Geological map of the Barberton greenstone belt, showing the distribution of the layered differentiated ultramafic complexes in the Onverwacht volcanic sequence. (Anhaeusser, 1975)

mafic and intermediate to acid volcanics, pyroclastics and chemical sediments. Ultramafic intrusive sills occur sporadically and are best developed at Msauli (17) and Havelock (18), Figure 2.8.

Overlying the volcanic sequences are the Fig Tree Group sediments comprising greywackes, shales, subordinate pyroclastics and tuffs. Overlying this sequence is an arenaceous sedimentary unit, the Moodies Group, a marginal marine and continental clastic sequence.

A comprehensive review of the nature of chrysotile asbestos occurrences within the layered ultramafic complexes of the Barberton Mountain Land is provided by Anhaeusser (1976a) (Figure 2.8).

The 16 km long Stolzburg layered complex contains basal serpentinized dunite and orthopyroxenite layers, with rodingite rocks occurring in the central portion of the complex. The serpentinized dunites are the host rocks to the chrysotile asbestos deposits, which are described by Hall (1930), van Biljon (1959, 1964), and Viljoen and Viljoen (1969c). A strong mineralization control is evident, with exploitable asbestos fibre occurring in dunites affected by prominent cross faulting and intraformational shear deformation. Folding of basal layers has localized fibre development in and around fold hinges in the Stolzburg mine. Differential intraformational movement took place between the serpentinized dunites and the more competent orthopyroxenite layers during deformation, which involved both faulting and folding. This produced dilationary zones in which fibre growth occurred.

The Koedoe ultramafic body has been folded into a tight syncline plunging about 60° northeast with a well developed north limb. Economic fibre is only developed in the hinge zone of the fold, with fibre confined to the lower dunite-peridotite layer. The fibre is developed in a stockwork of tension fractures which formed during development of the fold.

The Kaapsehoop ultramafic body is situated at the northwest end of the Jamestown schist belt within which the New Amianthus, Munnik Myburg and Sunnyside/Star asbestos mines are located (Hall, 1930; van Biljon, 1964; Anhaeusser, 1976b; Laubscher, 1963; 1983 a). This ultramafic body consists of a cyclic development of serpentinized dunite and orthopyroxenite layers. The body is folded into a syncline with an east-west fold axis, disrupted by several major faults. The ore zones of the New Amianthus and Munnik Myburg mines occur in the hinge zone of the folded host rocks. The ore zone of the Sunnyside/Star mine is developed along the southern, relatively undeformed limb of the syncline, adjacent to a major fault (Anhaeusser, 1976a). Chrysotile asbestos occurs as cross fibre in parallel to sub-parallel seams of the Ribbon Line and also as irregular seams in the Footwall Reef. Host rock control, source of serpentinous solutions, fibre growth mechanism and structural control are all clearly illustrated within this orebody (Laubscher, 1983a). The Ribbon Line occurs at the contact between the favourable host serpentinized dunite and peridotites (apple-green, green-brown, brown) and the overlying Godwan sediments. This line is a chrysotile asbestos horizon of parallel seams, with up to 40% fibre over a two metre width. The host rocks have been faulted and folded with initial fracturing and later tensional stress conditions enabling stockwork cross fibre to develop. Fractures within the Ribbon Line host rocks are parallel to the contact between the host rock and the overlying sediments, controlling fibre development into parallel and sub-parallel seams. Laubscher (1983 a) concludes that the favourable stress environment for fibre formation occurred after fracturing, in the final stages of tectonic activity.

The Msauli and Havelock ultramafic bodies occur in the south-eastern portion of the Barberton greenstone belt where several major chrysotile asbestos orebodies are located. Ultramafic lenses occur within the Swartkoppie Formation, the uppermost succession of the Onverwacht Group. The ultramafic bodies are differentiated and serpentinized with dunite, peridotite, pyroxenite and metagabbro units.

Barton (in press) has recognised a progressive change in composition of the Havelock ultramafic body consistent with fractional crystallization in a layered intrusion.

A number of major shears trend parallel to the strike of these bodies with a steeper dip (about 80°) than the ultramafic host formations (60-70°). These shears form part of the Maanhaar fault zone extending from the Havelock orebody, in the north-east, southwards into the Steynsdorp valley, a length of at least 20 km. The margins of the two ultramafic bodies are sheared which van Biljon (1959), Barton and Eaton (1980), and Barton (in press), interpret as a high angle tectonic zone along which the sill was emplaced as a solid, low temperature body. These writers conclude that the Havelock ultramafic sill is allochthonous and is either an Alpine-type body or has been derived from the crustal ultramafic succession of the Barberton greenstone belt. Paris (in prep.) has located several other high angle dislocation zones trending about parallel to the Maanhaar fault zone and related to it, suggesting that a series of tectonic pods or wedges are developed in the area. Emplacement as a solid body would have further deformed the sill resulting in fracturing and more complete serpentinization creating a more favourable host for later chrysotile asbestos fibre development. This may explain why economic cross-fibre is developed to a greater extent in these two bodies and not in many of the other layered ultramafic bodies of the Barberton area.

The sill is serpentinized at a relatively low temperature and pressure condition. The effect of this alteration has caused a distinct zonation with dark green varieties in the foot- and hangingwalls and a light green variety in the central portion. Economic fibre is mainly developed within the apple green serpentinized dunite-peridotite with a minor amount developed in the dark green varieties. The former variety has a higher MgO and lower Fe_2O_3 content than the dark green variety which accounts for the formation of a better grade of fibre. The fibre occurs mainly as cross fibre veins developed in tension gashes in which the parallel fibres are aligned normal to the vein walls in a massive stockwork of randomly orientated fibre veins.

The Rhodesian Craton contains two principal chrysotile asbestos producing areas: the Mashaba Igneous Complex and the Shabani ultramafic body. Comprehensive descriptions of both are provided by Laubscher (1963, 1964, 1968, 1983b). Wilson (1968) has described the Mashaba Igneous Complex while the geology of the Shabani ultramafic body has been well documented by Keep (1929) and Martin (1978). Anhaeusser (1976a) has reviewed both of these Precambrian ultramafic complexes.

The Mashaba Igneous Complex occurs at the western end of the Fort Victoria greenstone belt (Figure 2.5). It forms a predominantly ultramafic layered intrusion which can be divided into sheeted and dyke portions. This complex (Figure 2.9) appears to have been emplaced after the main folding phase of the area. It was intruded by an Archaean granite which Wilson (1968) suggests is of post-Shamvaian age (ca 2600-2900 Ma). The entire sequence was deformed with thrusting along the base of the sheet, intricate folding and faulting. The deformation resulted in the economic development of chrysotile asbestos fibre. Figure 2.9 illustrates the distribution of asbestos mines and prospects within the complex in relation to folding, faulting and thrusting. The majority of asbestos mineralization is located in fold hinges or on fold limbs. Gath's and King mines are the major producers within the complex where two fibre types are developed: namely, ribbon fibre (Gath's) and stockwork veins (King).

The Shabani ultramafic body is located on the northwest margin of the Belingwe greenstone belt, east of the Great Dyke (Figure 2.5). The Shabanie mine is the largest occurrence of chrysotile fibre in Africa, producing approximately 60 percent of Zimbabwe's asbestos. A number of disconnected orebodies are located in the central footwall dunite at the base of a lenticular differentiated ultramafic sill which has intruded into the Basement gneiss along the margin of the Bulawayan syncline (Laubscher, 1983b) at the northeast margin of the Belingwe schist belt. Laubscher (1963, 1968) considers this complex to be a post-Bulawayan intrusive similar in age to the Mashaba Igneous Complex. The sill has a strike length of 14 km (northwest-southeast), a thickness of about 1,5 km and dips 40° SW. This ultramafic body appears to have undergone a greater degree of magmatic differentiation than most other ultramafic bodies

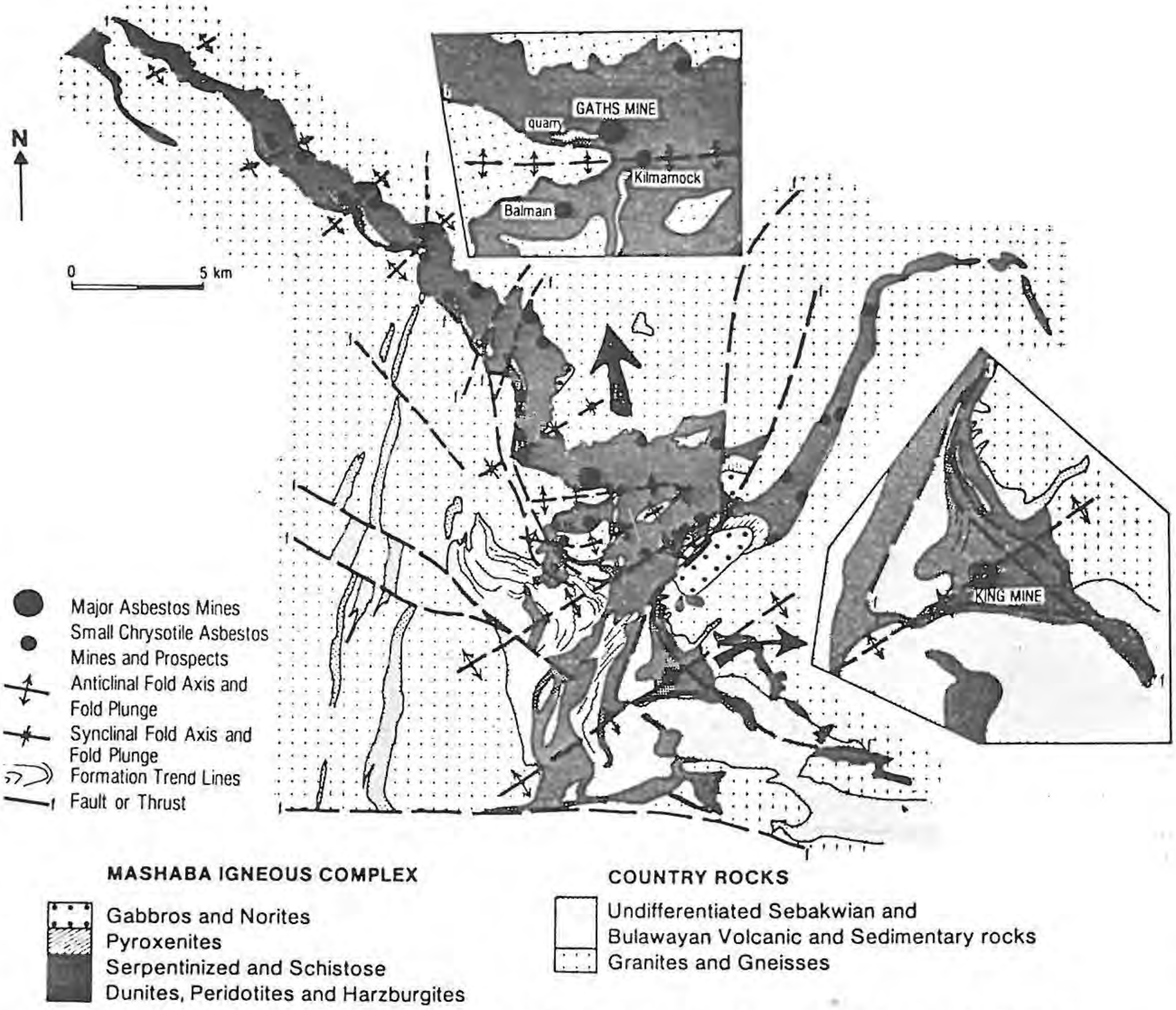


Fig. 2.9: Geologic map of the Mashaba Igneous Complex, Zimbabwe, showing the distribution of chrysotile asbestos mineralization with respect to faults, thrusts, and folds. (Anhaeusser, 1976 a)

in southern Africa, resulting in a major development of dunite at the base of the complex (Figure 2.10).

The ultramafic body was folded into shallow anticlines and synclines, followed by wrench and thrust faulting, with the development of extensive sympathetic slips, shears and fractures (Laubscher, 1983b). The dunite was extensively fractured sub-parallel to the gneiss contact with fracture spacing increasing away from that contact. Adjacent to the fractures, hydrothermal solutions, generated during deformation, altered

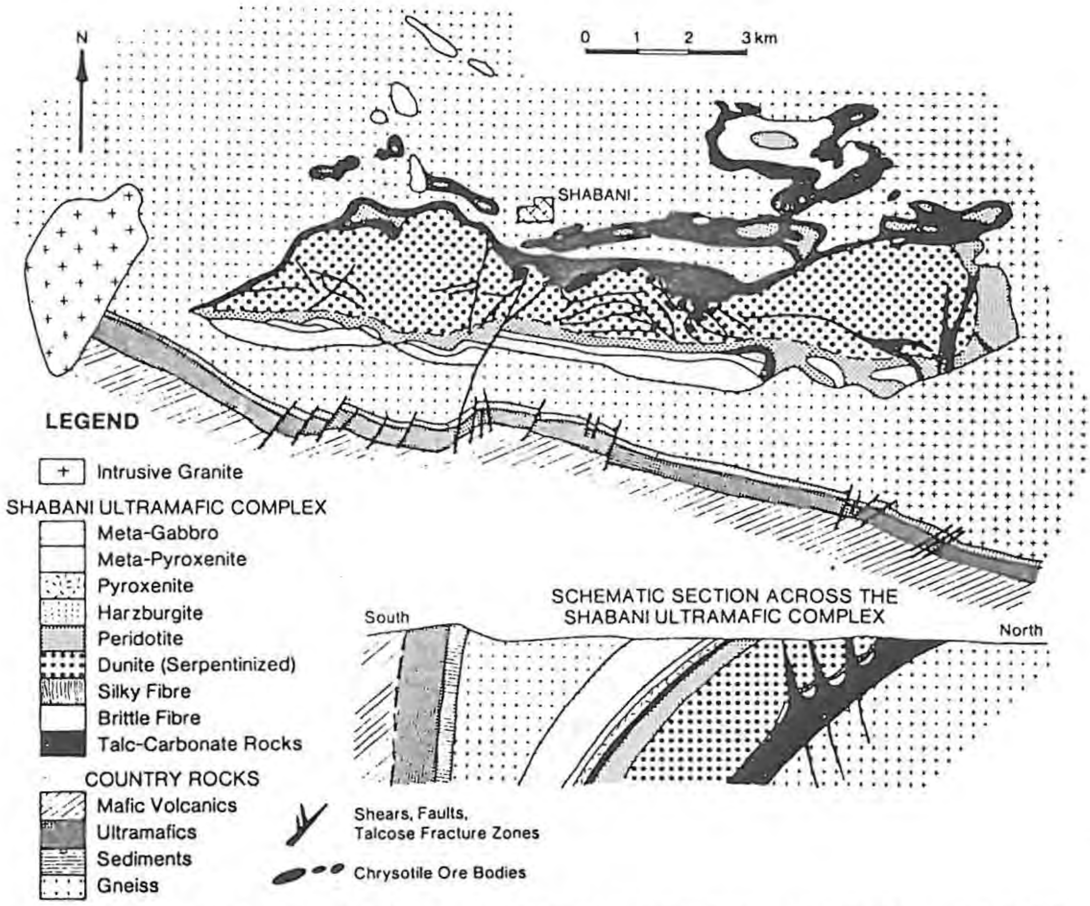


Fig. 2.10: Map of the Shabani Ultramafic Complex, Zimbabwe, showing the distribution of the main chrysotile asbestos orebodies. (Adapted from Laubscher, 1964).
(Anhaeusser, 1976 a)

the dunite to serpentine with the excess magnesium and silica going into solution to form serpentinous solutions. These solutions recrystallized to form economic chrysotile asbestos fibre deposits in favourable tensional stress environments. The orebodies are separated along strike and down dip by talc zones, developed in CO_2- metasomatized fractures and faults.

The Canadian chrysotile asbestos deposits of Ontario and Ungava in Quebec, are developed in Precambrian ultramafic complexes. The Ontario deposits have been described by Hendry and Conn (1957), Grubb (1962) and Rowbotham (1970). The Asbestos Hill deposit, located in the Ungava Peninsula has been described by Stewart (1976, 1978). Potential asbestos deposits in Ontario and Quebec have been briefly mentioned by Winson (1975) and Mann (1981).

The deposit in Munro Township, eastern Ontario, occurs within a narrow differentiated ultramafic sill-like complex, bounded by faults containing pronounced talc-carbonate alteration. The central core of the sill comprises highly serpentinized dunite, grading outwards into serpentinized peridotite, pyroxenite and gabbro. The orebody is bounded by a major cross fault to the west and a zone of talc-carbonate to the east. Seven major cross faults disrupt the sill and produce three sets of fractures within the orebody. These fractures are closely spaced in the central core of the sill and contain the majority of asbestos fibre veins forming an irregular stockwork pattern. Chrysotile asbestos veins are primarily associated with the light green, granular, dunitic core, with minor veins in the adjacent dark green, dense peridotite. Outside the ore zones the ultramafic rocks are composed of lizardite mesh textures after olivine producing pseudomorphs that reproduce the original cumulate textures. As the ore zone is approached, lizardite hourglass textures dominate over the mesh textures and these early retrograde textures recrystallize to form chrysotile serrate veins and antigorite + brucite prograde non-pseudomorphic textures, a similar sequence of events as observed in the Quebec Asbestos Belt (Winson, 1975; Mann, 1981).Hendry and Conn (1957) suggest that there was initial intrusion of this sill, then later differentiation into basic and ultrabasic units. Initial serpentinization occurred during cooling,with the development of an incipient fracture pattern produced by deformation of the sill during faulting and folding. Hydrothermal fluids formed concentrated serpentinous solutions within the sill which crystallized into chrysotile asbestos fibre in the fractures. Later CO_2- metasomatism produced talc- carbonate alteration of some serpentinite.

The Asbestos Hill orebody is developed within a folded Precambrian ultrabasic sill complex (Stewart, 1976, 1978) with the chrysotile asbestos occurring in a completely serpentinized dunitic unit. Considerable tectonic activity resulted in favourable structural conditions which culminated in the formation of the ore zone. The deposit consists principally of cross fibre gash-type veins of variable length, producing an orebody of exceptionally high grade. The fibre direction is both parallel and perpendicular to the layering of the sill complex, forming an irregular stockwork pattern. Stewart (1976, 1978) has proposed a sequence of events for the genesis of the fibre which are very similar to those suggested by Hendry and Conn (1957) for the Munro Township deposit.

Dolomitic limestones

Dolomitic limestone-hosted chrysotile asbestos fibre development requires a combination of three controlling factors, suggested by Button (1974, 1976). Firstly, an intrusive is required to supply heat to drive the metamorphic reaction of dolomite + silica + water → serpentine + calcite. Secondly, magnesia is supplied by dolomite, while silica is derived from chert in the dolomite. Thirdly, water is thought to be provided by the sill itself, and accounts for the fact that major deposits are limited to the upper surfaces of sills, the expected locus of accumulation of volatiles.

The upper metamorphic aureole of a sill is usually 1 to 2 metres thick, and consists of the assemblage serpentine, chrysotile, talc, and lime-rich carbonate. The control of chert is seen by the fact that only those sills intruded into chert-bearing dolomite are associated with fibre. Secondly, serpentine pseudomorphous after chert is common, and is seen as serpentine layers, laminae, and pods, duplicating the structure in chert.

Figure 2.11 illustrates a schematic section of the eastern Transvaal escarpment region with chrysotile asbestos fibre distribution above diabase sills intrusive into dolomitic rocks.

South African deposits of chrysotile asbestos are developed in the Malmani Dolomite Subgroup of the Transvaal Supergroup. High-quality chrysotile asbestos has been mined on a small scale at numerous localities in the Transvaal Basin with the principal deposits described in detail by Hall (1930), van Biljon (1959, 1964), Button (1974) and summarised by Anhaeusser (1976a). They are located in the eastern Transvaal in the

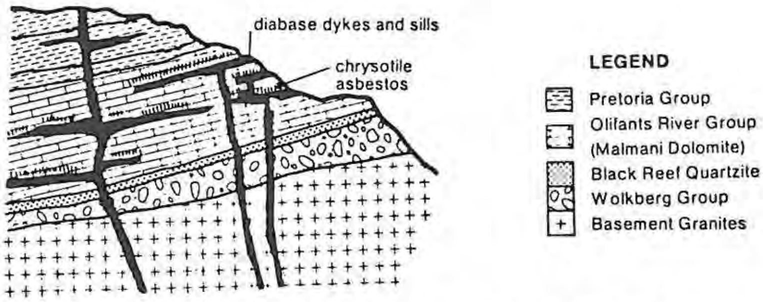


Fig. 2.11 : Schematic section illustrating the distribution of chrysotile asbestos mineralization above diabase sills intruded into dolomitic rocks of the Transvaal Supergroup. (Anhaeusser, 1976 a)

escarpment regions to the west of the Barberton Mountain Land (Figure 2.8) where abundant Bushveld-age sills and dykes (ca 1950 Ma) are intrusive into the dolomite. The fibre typically occurs at the upper contact of mafic sills intrusive into the Malmani Dolomite. Smaller deposits are found adjacent to dykes. The dolomite is serpentinized in these alteration zones, with the serpentine clearly pseudomorphous after chert, inheriting its nodular form. The serpentine frequently displays delicate depositional structures such as ripple marks, algal laminations and stromatolites (Button, 1974; Anhaeusser and Button, 1974). Chrysotile asbestos fibre is developed within the serpentine with fibre development related to minor deformations in the dolomite (van Biljon, 1964). The thermal reaction of the dolomite and fibre formation occurs at temperatures below 500°C.

Rowbotham (1970) has described chrysotile asbestos fibre formation in the Salt River and Sierra Ancha regions of Arizona where it is developed in narrow bands associated with diabase sills.

No such chrysotile occurrences have been reported from the Hamersley Basin. They are likely to be present where mafic sills intrude cherty phases of the Wittenoom and Carawine dolomites (Button, 1976).

The only chrysotile asbestos developed in the U.S.S.R. occurs near Aspargash just south of Krasnovask on the Yenesei river (Mann, 1981). This shelf sedimentation represents the terminal stage of relatively small Archaean - Proterozoic geosynclinal cycles developed between the West Siberian and Siberian Platforms (Figure 2.3).

Shao-Ying et al. (1980) mention cross fibre chrysotile asbestos deposits developed in serpentinized dolomites in southern China. Wen (1980) describes these deposits as medium to small with fibre contents ranging between 1,5 - 4%, the latter grade found at Jinzhao mine, Liaoning Province. The fibre quality is good with a low iron content. These dolomite shelf sequences represent the terminal geosynclinal stage of evolution of the southwestward extension of the Transbaikal-Maritime region of the far western U.S.S.R. (Figure 2.3, (6)).

Structural Control

General deformation of the host rock in the form of faulting, fracturing, folding and shearing plays a major role in the localizing of asbestos deposits. The various fibre- controlling factors are intimately related with folding the dominant regional factor whereas faulting and fracturing provide a more localized control governing fibre growth and fibre density. Small intrusives also contribute to the general fracturing and opening up of the rock. This leads to the alteration of the host ultramafic rocks through the process of serpentinization and ultimately to the formation of chrysotile asbestos fibre in favourable stress environments.

Chrysotile asbestos has been recognised by many writers as a stress-controlled mineral so that, without the requisite structural deformation, even the most ideal dunite or peridotite host rock will be unsuitable for the development of fibre. Systematic structural studies in many asbestos deposits throughout the world have shown that cross fibre asbestos seams (veins) require tensional stress conditions for fibre growth, whereas slip fibre is localized in shear planes (Hall, 1930; Cooke, 1937; Proud and Osborne, 1952; Riordon, 1955; Laubscher, 1963; 1964; 1968; 1980a; van Biljon, 1959; 1964).

Emphasis has largely been placed on faulting of various types as the principal structural control for fibre localization. Laubscher (1968, 1980a) summarized the main features of structural control as being: 1) the formation of fractures in which stress-controlled dilation seams can form and from which serpentinization can take place; 2) the development of thrust faults, wrench faults and shear zones, the latter acting as channelways for hydrothermal solutions essential for the serpentinization of the potential fibre host rocks. Areas where stress-controlled dilation seams could develop are associated with the faulting. Significantly, fibre is best developed in those areas having the simplest structural pattern; 3) slip fibre is localized in the fault zone or sympathetic structures where wrench faulting is dominant; 4) the presence of structures which create the correct stress environment, allowing the serpentine minerals to recrystallize to form fibre seams.

Anhaeusser (1976a) acknowledges that faulting and fracturing are largely responsible for the local development of asbestos fibre but clearly demonstrates that folding is often a dominant regional controlling factor in the localization of asbestos mineralization in ultramafic rocks (Figure 2.9). Stewart (1976, 1978) confirms this control on mineralization in the Asbestos Hill orebody, Canada. Keep (1929) considered that initial fracturing of the Zimbabwe ultramafic bodies was due to contraction on cooling with later deformation by faulting and folding.

Laubscher (1964) illustrates the structural control on fibre formation with the zone of fibre enrichment developed in the area of localized tensional stress. Fibre growth is sub-parallel to the direction of tensional stress, the growth following the line of least resistance (Figure 2.12).

Winson (1975) and Mann (1981) conclude that the majority of chrysotile deposits occurring in tectonic domains tend to occur in serpentinized peridotite rather than dunitic host rocks. This is probably due to the fact that serpentinized dunite bodies tend to become ductile when subjected to stress thereby aiding in the development of fracturing in the surrounding, more competent, brittle peridotite which then becomes a favourable site for later fibre development.

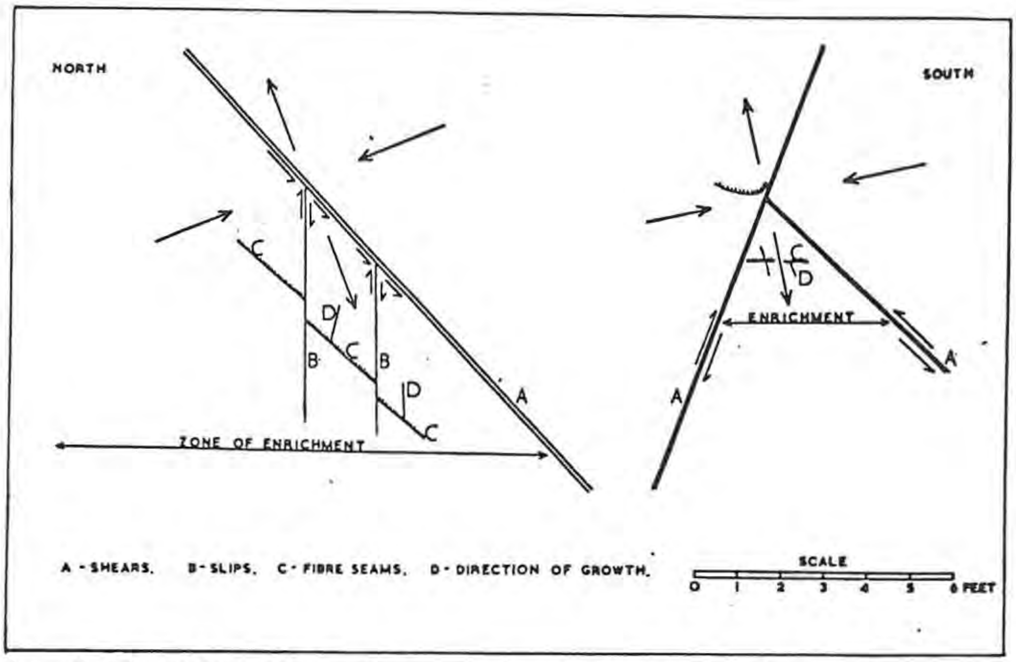


Fig. 2.12: LOCALIZED STRUCTURAL CONTROL OF FIBRE FORMATION
(Laubscher, 1964)

Alteration of Ultramafic Rocks

A specific combination of faulting, shearing, folding, serpentinization and metamorphism is required for the formation of chrysotile asbestos. Thus, not all serpentinized ultramafic rocks contain asbestos deposits. Wicks (1980) describes the alteration of a peridotite body through retrograde and prograde metamorphism with the various mineral assemblages produced according to the prevailing temperatures. During retrograde metamorphism the region of serpentine stability (antigorite) is reached at about 500°C wile below 300°C serpentinization is characterized by the pseudomorphic replacement of the original minerals by lizardite with or without minor chrysotile. During prograde metamorphism a similar cycle of mineral assemblages is formed until the original assemblage is reached. Details and complexities of ultramafic alteration are found in O'Hara (1967), Moody (1976), Evans (1977), two papers by Hemley et al. (1977), Wicks and Whittaker (1977) and Wicks et al. (1977).

Ultramafic complexes are composed of dunite, harzburgite and lherzolite (Wyllie, 1967) with the major minerals comprising olivine, orthopyroxene, clinopyroxene and chromite. The rate of alteration has been found to be olivine > orthopyroxene > clinopyroxene, probably reflecting a different rate of alteration of the minerals in a lower temperature and pressure environment. Several writers (in Moody, 1976) have shown that the common hydrated equivalents of ultramafic rocks contain lizardite > chrysotile, brucite and magnetite. The brucite content defines a lower temperature of serpentinization of olivine-rich peridotites and does not form from the alteration of pyroxene- rich peridotites.

The serpentinization process

Most ultramafic rocks are hydrated to form partially or completely serpentinized rock. The term serpentine is used as the family name of the three major minerals : lizardite, chrysotile and antigorite. Moody (1976) reviews the serpentinization processes in ultramafic rocks which many writers have recently discussed. The main points of contention are: (1) the differences between the reaction of dunite and pyroxenite with the fluid phases; (2) the temperature-pressure regime of hydration; (3) the mineral assemblages produced during serpentinization; (4) whether serpentinization occurs at constant volume or constant composition, or as a combination of both conditions; (5) the influence of fluid composition on hydration and mineralogy of the serpentinite; (6) the origin of the serpentinizing fluids.

Iron in olivine is redistributed during serpentinization and can either enter the structure of the serpentine minerals or brucite (where Fe replaces Mg) or form separate opaque mineral phases, namely : magnetite, awaruite, pentlandite or ferrit-chromite (Moody, 1976). Magnetite is produced chiefly from the serpentinization of dunite, and is correlated with increased temperature at low oxygen fugacities. Lower temperatures of serpentinization favour iron substitution with brucite (and lizardite) rather than the formation of magnetite.

Antigorite formation predominates in alpine-type ultramafic rocks and can replace pre-existing lizardite or chrysotile when the serpentinite has undergone early prograde metamorphism to upper greenschist or lower amphibolite facies. Antigorite can also form during late stage retrograde metamorphism (Wenner and Taylor, 1974). Chromite may be replaced by secondary magnetite or ferrit-chromite which indicate that the serpentinite has undergone a higher temperature - pressure metamorphic event than is required for the formation of lizardite and chrysotile serpentinites.

The process of serpentinization is dependent on the existence of an interacting, aqueous fluid phase. Introduction of water into an anhydrous rock causes a decrease in the density of the rock and a concomitant increase in the volume of the rock mass unless material is removed in solution. There is evidence for serpentinization at constant volume or constant chemical composition but occurring under different conditions (Moody, 1976). The volume increase possible during serpentinization may assist in the intrusion of the serpentinite along zones of structural weakness. The change in chemical composition at constant volume implies an open system with free exchange between the fluid and ultramafic rock during serpentinization. Once the ultramafic rock has access to an aqueous fluid, the effect of temperature (less than 400°C) and pressure will be minimal except to influence the rate of serpentinization.

Barnes and O'Neil (1969) have classified the fluids relating to serpentinization into three types on the basis of their chemistry and isotopic compositions. The waters are characterized by a high pH ($>$ 10), low Mg concentrations and high chloride content. Such fluids are reactive and have the possibility of containing significant quantities of dissolved silica. The chemical properties of the fluid, temperature and pressure determine the elements which may be leached from the ultramafic rock and possibly transported by the fluid. These fluid properties determine the mobility of elements during serpentinization and they do not indicate a widespread removal of Mg and Si from the ultramafic rock. The accessibility of water to the ultramafics can be increased by shearing, fracturing and faulting which increases the surface area and, thus, the rate of serpentinization. The alteration can be significantly increased if fresh fluid has continual access to the rock body in an open, highly sheared environment.

Johannes (1969) has shown that the CO_2 content of the serpentinizing fluid must be low because chrysotile or lizardite are not stable with respect to talc in the presence of a CO_2 - bearing fluid. Brucite alters readily to magnesite while antigorite is stable to a much higher CO_2 content. This replacement of serpentine - brucite by talc-magnesite is termed talc-carbonate alteration which occurs after serpentinization. This alteration follows a local joint or fracture pattern which act as conduits for the CO_2 - bearing fluids.

Faust et al, (1956) have shown that the boron content of ultramafic rocks is greater in the serpentinite than in the parent rock which indicates a possible sea-water origin for some of the fluids involved in serpentinization. These concentrations may also indicate the temperature of serpentinization as boron partitions into serpentine at temperatures less than 200° C.

Stable isotope geochemistry has also been used to deduce temperatures of serpentinization and to provide evidence on the origin of the serpentinizing fluids. Wenner and Taylor (1971) derived an approximate serpentine - magnetite geothermometer for the various serpentine minerals. This geothermometer yielded the following temperatures: continental lizardite and chrysotile, 85-115°C; oceanic lizardite, 130°C; oceanic chrysotile, 185°C; oceanic antigorite, 235°C and continental antigorite, 220-460°C. Evans (1977) suggests that the development of calcium-rich rodingite is indicative of low temperature lizardite-chrysotile serpentinization which is associated with chrysotile asbestos formation.

Wenner and Taylor (1973) compared mid-ocean ridge serpentinites and continental ophiolite complexes and concluded that different waters were involved in the serpentinization of the two types of ultramafic body. They found that ophiolite complexes were largely unserpentinized prior to their continental emplacement. Wenner and Taylor (1974) showed that lizardite-chrysotile serpentinization is most probably caused by waters of meteoric-hydrothermal origin while antigorite serpentinites are formed during regional metamorphism in the presence of non-meteoric waters.

Serpentinite bodies exhibit esentially ductile behaviour at temperatures of 100°C or higher at moderate pressures of 2-4 k bar (Wenner and Taylor, 1971). These bodies only become brittle at relatively small confining pressures (< 2 k bar) and low temperatures. Most serpentinite bodies, therefore, may only be extensively fractured in very near - surface environments. The brittle fracturing of the ultramafic bodies is essential for fluid access to increase the rate of serpentinization. It is also essential for the conditioning of the host rock to allow access to later generated hydrous magnesium silicate solutions which will form fibrous chrysotile asbestos veins on recrystallization.

Moody (1976) has summarized the process of serpentinization where alteration of an ultramafic rock produces the assemblage : lizardite, chrysotile, magnetite, $\pm$ brucite, $\pm$ antigorite with minor awaruite. Lizardite - chrysotile serpentinites are widespread in comparison to antigorite serpentinites. The iron originally present in olivine or pyroxene redistributes during serpentinization and enters solid solution in serpentine minerals or brucite or forms an opaque phase, most commonly magnetite. The presence of antigorite and ferrit-chromite indicates that the serpentinite has undergone prograde or retrograde metamorphism. Temperature and pressure conditions imply an upper crustal environment for most serpentinization and locally, within the ultramafic bodies, a very low oxygen fugacity. A high iron content of brucite indicates a temperature of serpentinization well within the stability field of serpentine-brucite. The fluid involved in serpentinization may be any aqueous CO_2- poor fluid. The fluid becomes extremely alkaline with continued alteration of the ultramafic rock. The boron enrichment in serpentinized rocks indicates a possible sea-water origin for some of the fluids involved in serpentinization. The stable oxygen and deuterium isotopic work on serpentinites demonstrates a different type of water and temperature of formation for lizardite - chrysotile in comparison to antigorite serpentinites. The temperature ranges of serpentinization were estimated as: continental lizardite - chrysotile, 85-115°C; oceanic lizardite - chrysotile, 130-185°C; oceanic antigorite, 235°C; continental antigorite, 240-460°C. These temperatures imply that antigorite, chlorite and talc typically forms under deeper-seated conditions. Most serpentinite bodies may only be extensively fractured in very near surface environments where they become brittle at low temperatures and relatively small confining pressures. The brittle fracturing of the ultramafic body, alteration to lizardite - chrysotile serpentinite and recrystallization of later generated hydrous magnesium silicate solutions are all essential parameters for the development of chrysotile asbestos veins. The rate of serpentinization appears to be limited, however, by the availability of serpentinizing fluids rather than the temperature of the process.

Wicks and Whittaker (1977) have divided serpentinization processes into eight types depending on whether the conditions involve, or do not involve, rising temperatures, presence of substantial shearing, and nucleation of antigorite. They recognized three main regimes of temperature which correspond to the stability of different serpentine mineral and brucite assemblages, the redox condition during serpentinization, and the conditions required for the formation of chrysotile asbestos deposits (Table 2.1).

CONDITION INVOLVED	TYPE OF SERPENTINIZATION PROCESS			
	Type 3	Type 5	Type 6	Type 7
Temperature	Falling or constant.	rising	rising	rising
Substantial shearing	absent	absent	present	absent
Antigorite nucleation	absent	absent	absent	present

TABLE 2.1: Conditions and types of serpentinization processes required for chrysotile asbestos formation: (Compiled from data after Wicks and Whittaker, 1977)

Type 3 appears to be the most common process with serpentinization of olivine forming mesh rims and occasionally pure hourglass textures. Fibrous and non-fibrous veins of lizardite and/or chrysotile, with or without brucite, are associated with these textures. Type 5 process most frequently produces hourglass textures which are associated with significant amounts of chrysotile asbestos. These asbestos veins are associated with non-fibrous chrysotile veins, or lizardite with or without brucite. Type 6 process occurs where shear zones are adjacent to serpentinized ultramafics containing pseudomorphic textures. The latter are invariably fractured and contain abundant fine chrysotile asbestos veins. The Coalinga asbestos deposit, California, (Mumpton and Thompson, 1975) is the ultimate example of this type. Type 7 is a common process with chrysotile asbestos veins formed. Veins of non-fibrous chrysotile and/or lizardite, with or without brucite are associated with this type. Antigorite with brucite textures of Type 7 are often associated with chrysotile, with or without brucite, textures of Type 5 within the same ultramafic body, which is usual in chrysotile asbestos deposits. Jeffrey mine, Eastern Townships of Quebec, Canada, is an example.

Serpentine textures

Olivine is known to alter to serpentinite with a characteristic mesh or hourglass texture (Wicks, 1971; Wicks and Whittaker, 1977; Wicks et al., 1977; Wicks, 1980). Chrysotile asbestos deposits are characterized by a specific association of textures (Grubb, 1962) which have been studied in detail by the above writers. The textures suggest that asbestos deposits are confined to serpentinites formed under specific metamorphic, structural and mineralogical conditions.

The serpentine mineral textures can be divided into primary and secondary textures. Primary textures are characterized by recognizable pseudomorphs after the original minerals, and secondary textures are characterized by interlocking or interpenetrating features that obliterate the outlines of the original minerals or their pseudomorphs (Wicks, 1971).

During the course of normal primary serpentinization, olivine (forsterite), pyroxene (enstatite) and amphiboles are pseudomorphically replaced by lizardite, or lizardite and brucite. Olivine produces mesh texture pseudomorphs as idealized in Figure 2.13, while the pyroxene and amphiboles alter to bastites. The lizardite, with or without brucite, begins to form at fractures and grain boundaries and advances to form a mesh rim around a relict olivine core (Case 2, Figure 2.13). The mesh rim can continue to develop until all the olivine is consumed and an hourglass texture of lizardite, or lizardite and brucite, is produced (Case 1, Figure 2.13). More frequently, however, the relict olivine centres are replaced by randomly orientated serpentine (Case 3, Figure 2.13). Antigorite and chrysotile also form primary pseudomorphic textures, but they are less common and form under more restricted conditions than the lizardite primary textures.

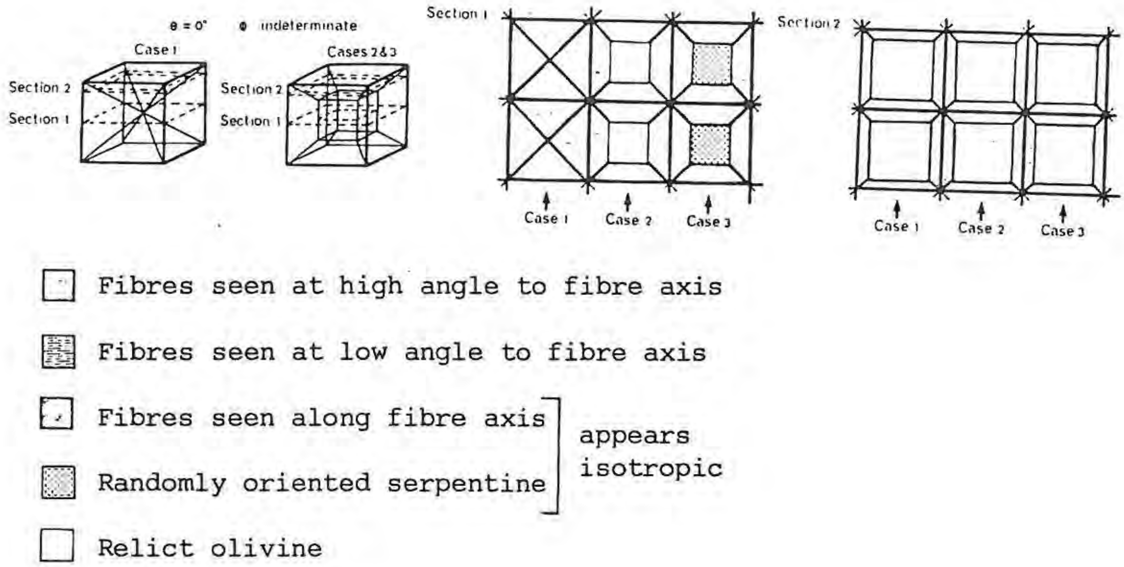


Fig. 2.13: Idealized mesh and hourglass textures after olivine. Cubes of olivine are assumed to be replaced by orientated lizardite growing at an equal rate on all cube faces. In Case 1 no olivine remains, in Case 2 a core of olivine remains and in Case 3 randomly orientated lizardite is formed.

(after Wicks & Whittaker, 1977; Wicks, 1980)

Magnetite is usually produced by the serpentinization of olivine. During the early stages of this process the magnetite is fine grained and dispersed through the rock imparting a black, grey, brown or dark green colour. With advanced serpentinization the magnetite migrates to form coarse aggregates and the rock becomes green. Retrograde serpentinization often produces a minor amount of chrysotile asbestos, but the most abundant type of vein is massive, sometimes apple green serpentine, which is a mixture of lizardite and non-fibrous chrysotile. None of the known asbestos deposits occur in retrograde serpentinized ultramafic rock.

Secondary serpentine textures are produced by the recrystallization of the primary serpentine textures and the replacement of any relict primary minerals still present. The secondary textures most commonly take the form of a random mass of interlocking grains or a random to oriented mass of interpenetrating blades. The most abundant serpentinite of prograde metamorphism is composed of antigorite, with or without, magnetite and represents a fairly high degree of metamorphism near the upper limits of the serpentine stability field (Figure 2.14).

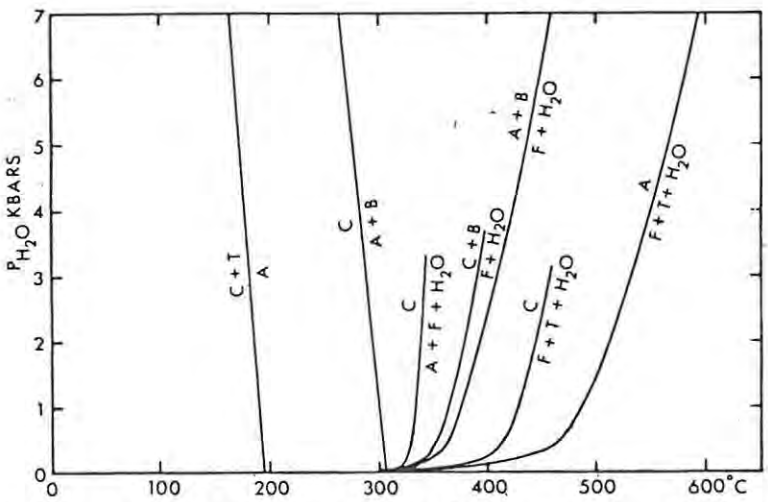


Fig. 2.14: Temperature-pressure (P_{H20} = P_{total}) diagram for serpentines. A = antigorite, B = brucite, C = chrysotile, F = forsterite. L = lizardite, T = talc, modified after Evans et al. (1978) (Wicks, 1979)

The antigorite forms either through the recrystallization of lizardite pseudomorphic textures or directly through the replacement of relict olivine, pyroxenes and amphiboles. The antigorite usually forms as elongate blades which form xenoblastic, inter-penetrating textures that obliterate the original pseudomorphs. Antigorite-brucite textures occur less frequently and lizardite, with or without, chrysotile, also forms interlocking secondary textures. Chrysotile forms replacement veins (serrated veins), hourglass and mesh textures. The rocks formed by these antigorite textures are usually harder and tougher than the retrograde, lizardite, pseudomorphic rocks, and are grey to green depending on grain size and distribution of the magnetite.

Serpentinites that have been involved in regional, dynamic or thermal (prograde) metamorphism are composed of secondary antigorite interpenetrating textures. When veins do occur, they are composed of antigorite, as chrysotile and lizardite are not stable at these temperatures. The rare occurrence of chrysotile asbestos veins in these rocks is due to vein formation after the height of the metamorphism when conditions have lowered into the chrysotile stability field.

Textures in asbestos deposits

Chrysotile asbestos deposits develop in a limited portion of the prograde metamorphic regime below the antigorite regime. If metamorphism is too intense, only antigorite will form. If there is no metamorphism only minor amounts of chrysotile asbestos will form. Thus, a mild metamorphism, together with faulting, fracturing, shearing or folding, is required to produce asbestos deposits.

The serpentinites within asbestos deposits are composed of a variety of textures and serpentine minerals. Pseudomorphic textures of lizardite after olivine and pyroxene may be present but lizardite hourglass textures after olivine dominate over lizardite mesh textures. Secondary interlocking and interpenetrating textures of lizardite, chrysotile and antigorite replace the lizardite hourglass and mesh textures. The chrysotile and lizardite secondary textures tend to dominate the antigorite secondary textures, but some chrysotile asbestos deposits only contain antigorite or antigorite and brucite secondary textures. Magnetite is commonly, but not always, present in these textures. Any given deposit may contain one or several of these textures and assemblages (Grubb, 1962; Wicks and Whittaker, 1977). When fibrous chrysotile forms non-pseudomorphic serrate veins it may produce mass-fibre if it completely replaces the earlier minerals. This is a minor source of asbestos since the rock is actually composed of asbestos, but it is difficult to obtain a high recovery from this type of ore. Examples of this mass fibre type are found at the Marbestos mine, Barberton greenstone belt, Eastern Transvaal (Anhaeusser, 1976) and Coalinga, California (Mumpton and Thompson, 1975). Cross and slip fibre chrysotile asbestos veins are present in serpentinized ultramafic bodies as the final phase of alteration, usually cross cutting all other earlier formed mineral assemblages and textures.

Serpentinous Solutions

Laubscher (1964, 1980a, 1983b) describes a serpentinous solution as a hydrothermal solution containing magnesium and silica, from which serpentine minerals can crystallize. The serpentinization of olivine by hydrothermal solutions causes excess magnesium and silica to form the serpentine solution. Frick and Greef (1978) confirmed that the formation of veins of chrysotile, which may eventually crystallize to asbestos fibre under favourable conditions, took place after the serpentinization of the olivine within ultramafic host rocks. They found that textural evidence from some serpentinized ultramafics also indicate that the serpentinous solutions have been derived from the olivine pseudomorphs in the vicinity of asbestos veins suggesting that these solutions were reasonably viscous. Laubscher (1963) showed that the majority of the material for fibre growth has been derived from the sidewalls, by using magnetite as a marker, and not from external sources such as meteoric waters as proposed by some writers. This evidence implies that the serpentinous solutions are derived from the serpentinized host rock and are redistributed through suitably fractured portions of the body. Crystallization of these solutions in a fibrous form occurs under favourable tensional stress conditions, forming stress-controlled dilation seams.

Laubscher (1963) has found that the lack of hydrothermal activity has prevented the formation of asbestos fibre bodies, although the other two factors (host rock and structural control) may have been satisfied.

It is thus important that the source of solution must be established. Van Biljon (1964) proposed that serpentine would go into solution in areas of pressure and migrate to low tensional pressure areas. Laubscher (1983b) confirms that this has occurred at King mine where the serpentine in the shear zones has been subjected to pressure with the origination of serpentinous solutions in these areas. The presence of hydrothermal solutions has assisted this process which provides greater mobility to the fluids. Laubscher (1983a) suggests that certain serpentinites are more susceptible to dissolution than others, as observed by the distinct host rock control at the New Amianthus mine. Serpentinous solutions, from which the fibre crystallized, were derived from underlying sheared serpentinite and migrated to low tensional pressure areas. Host rock control, thus consists of the source of serpentinous solutions and the chemically favourable side-wall initiating surface for fibre growth.

Laubscher (1964) established that the solutions which caused the serpentinization and steatization of the host ultramafic rocks were of hydrothermal origin due to: 1) the presence of carbonate in the ultrabasic rocks, shear zones, aplites and pegmatites; 2) the intimate association of quartz and pegmatites in the talc zones; 3) sulphide and gold mineralization in the altered ultrabasics which is not present in the relatively unaltered portions; 4) the increasing width of footwall talc with depth; 5) no evidence to suggest that the above alteration processes are related to weathering or to the action of meteoric waters.

Carbon dioxide is a minor constituent in the initial stages of hydrothermal activity but becomes a major constituent in the later stages when talc-carbonate alteration engulfs former serpentine and fibre veins, especially adjacent to channelways. This alteration of original fibre results in the development of uneconomic brittle fibre.

Frick and Greef (1978) consider that the leaching of the serpentinite is best accomplished by acid solutions containing either Cl^- or SO_3^{2-}. Pundsack (1955) and Winchel (1962) have shown that the brucite outer layer of the chrysotile fibril dissolves readily in acid solutions but appears to be more stable in alkaline solutions. Lizardite was found to dissolve less readily than chrysotile in acid solutions but more easily than antigorite. Chrysotile and brucite would thus be able to dissolve in a dilute acid solution and yield a hydrated magnesium silicate gel, the serpentinous solution necessary for fibre formation.

Van Biljon (1959) suggests that the most favourable temperature of the solution for chrysotile asbestos formation is about 400°C. This asbestos can be expected to form at all depths at which serpentine is stable, provided that the favourable tension stress conditions and sufficient serpentinous solutions are available. No fibre will form if the temperature is too high and insufficient solution is present. He does not regard the source of the solutions to be of primary importance although their presence is necessary for fibre formation. Vedernikov (1980) calculated the temperatures of chrysotile asbestos formation in the Russian deposits of Bazhenovo, Sayansky and Aktovrak, using Wenner and Taylor's (1971, 1974) isotopic geothermometer method. He found that the formation temperatures of the hydrous magnesium solutions ranged between 190-200°C which are considered to be low temperature deposits.

Hendry and Conn (1957) describe the Munro deposit which indicates that the ore solutions, consisting initially of hot waters, were injected into the fractures traversing the partially serpentinized peridotite. They penetrated and dissolved the walls of these fractures and eventually became saturated with magnesium silicate. The fractures were held open by the solutions under high pressure, and these serpentinous fluids were injected into any new fractures formed during the period of fibre formation. Gradual lowering of the temperature of the solutions produced supersaturated solutions of magnesium silicate and crystallization of chrysotile asbestos fibre.

Stewart (1976), in describing the formation of the Asbestos Hill orebody, indicated that ductility contrasts between the weaker serpentinized dunite and more competent pyroxenite layers resulted in the formation of tension fractures and shears in the dunite during deformation. Magnesium silicate solutions were subsequently injected into these fractures and crystallized into cross-fibre veins of chrysotile asbestos during conditions of favourable temperature and pressure.

Asbestos Veining

The characteristics of asbestos veins have been described by Riordon (1955), Laubscher (1968, 1980a, 1983b), Winson (1975), Laurent (1975b) and Mann (1981), and illustrated in Figure 2.15.

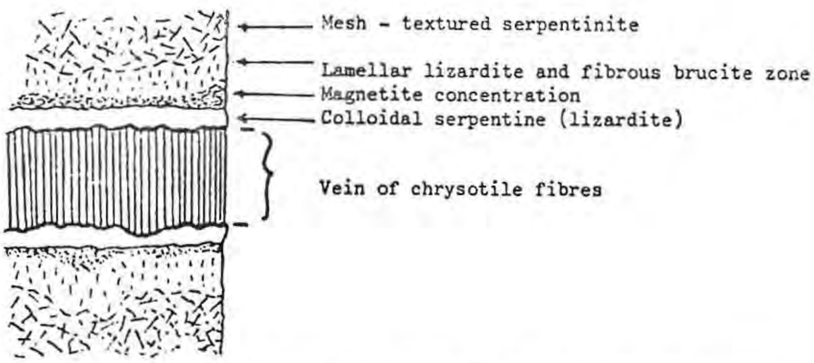


Fig. 2.15: Idealized section through an asbestos vein (Laurent, 1975 b).

Chrysotile asbestos occurs as cross-fibre veins in which the fibres are parallel and normal to the vein walls, or as slip-fibre in which the fibres lie in near-parallel arrangement along the plane of the vein, usually a shear plane. Mass-fibre is an aggregation of variously orientated fibres or stellate groups of radially arranged fibres. The Coalinga deposit in California has a unique variety of mass-fibre, termed platey fibre.

The fibre in the veins may be straight, gently curved or contorted. Kinks in the fibre represent potential weakness where it breaks during milling (Figure 2.16). The kinks are caused by post-fibre movements within the host rock. Crenulations often create a potentially weaker fibre and an increase in fibre-to-fibre cohesion because of the interlocking effect.

Most cross-fibre veins are split by one or more partings about parallel to the vein walls which shortens the length of the fibre relative to the vein width. Partings occur either as microscopic discontinuities or as irregular shaped inclusions composed of picrolite, talc, serpentine, brucite, and magnetite, or as combinations of these inclusions. Inclusions, usually colloidal serpentine and magnetite, often form between the vein sidewalls and the fibre which influences the degree of cohesion the fibre has with the sidewall (Figure 2.15). Low cohesion enables the fibre to be easily separated from the sidewalls during beneficiation.

The veins may be irregular, infilling several fracture sets, forming a stockwork pattern. These veins may be relatively persistent or short and lenticular. Veins occurring in parallel joint or fracture sets are known as ribbon fibre. The veins may be fissure fillings, replacement fibre or stress-relief features and are often the result of a combination of these processes. The fibres of intersecting veins may coalesce, or there may be a confused mixture of magnetite, picrolite and fibre. At some intersections the fibre of the marginal portion of one vein may merge with the marginal portion of the other vein. Fibre may grade into picrolite either laterally or along the length of the vein. In places the fibre may lens out, terminate abruptly or fade into the wall rock, without any gradual decrease in width. Fibre veins may, thus, be simple, split by partings or are composite.

Fibre Genesis

Numerous writers have proposed hypotheses to explain asbestos fibre genesis, which are discussed in Cooke (1937), Riordon (1955, 1962), van Biljon (1959), and Laubscher (1963). Riordon suggested that the process of chrysotile fibre formation was a combination of fissure filling and wall rock replacement. However, this does not explain the mechanism of fibre growth and the controlling factors, which are described by Laubscher and Laurent (1975b).

Riordon (1955, 1962) comprehensively describes the genesis of chrysotile asbestos fibre from observations in the Thetford-Black Lake District of Quebec. Field and laboratory evidence suggests that the original vein serpentine was in an amorphous state and that the veins are usually of a composite nature, resulting partly from fissure filling and partly from wall rock replacement. Picrolite (a green compact, banded and ofter coarsely fibrous, serpentine) and asbestos were derived through crystallization of this vein material and two stages of crystallization were involved. The first gave rise to picrolite and the second resulted in the conversion of picrolite to asbestos. Laubscher (1963) confirms this conversion at the Shabanie mine, and the writer (Abbott, 1981) also observed this gradation in drill core during exploratory drilling. Amorphous serpentine grades into banded fibre within the veins suggesting a form of colloidal replacement. Analyses show that the uncombined water content in these veins is considerably higher than the normal wall rock serpentine which suggests that the evolution of the fibre is by a later process which transformed the amorphous serpentine.

Riordon (1955) describes two hypotheses for the origin of the veins as proposed by various writers. One hypothesis is that the fibres have growth between the walls of the original fractures; the other is that fibres grew by wall rock replacement. He is of the opinion that fracture filling occurred. Minor unmatched irregularities in the wall and the presence of relict wall rock fragments in the vein margins indicates that there has been some growth by wall rock replacement. Thus both processes are operative, with one or other predominating in any particular vein.

Laurent (1975b) observed that tensile and shear fractures were often synchronously filled, as they were progressively opened, with crystals of fibre derived by solution or diffusion from material of the wall rock. In the veins the orientation of the growing fibres is not controlled by the position of the wall rock but by the direction of minimum shear stress. Expansion causes fibre growth and the growing fibres cause dilation. Significant changes in the direction of minimum shear stress are expected to produce changes in the direction of fibre growth. Such changes are reflected by kinks in the fibres.

Fibres are formed by a process of diffusion and solution transport during the progressive opening of dilation fractures. Simple asbestos veins have formed by syntaxial growth, the veins with a median suture have formed by antitaxial growth and composite veins have formed by a combination of syntaxial and antitaxial growth (Figure 2.16).

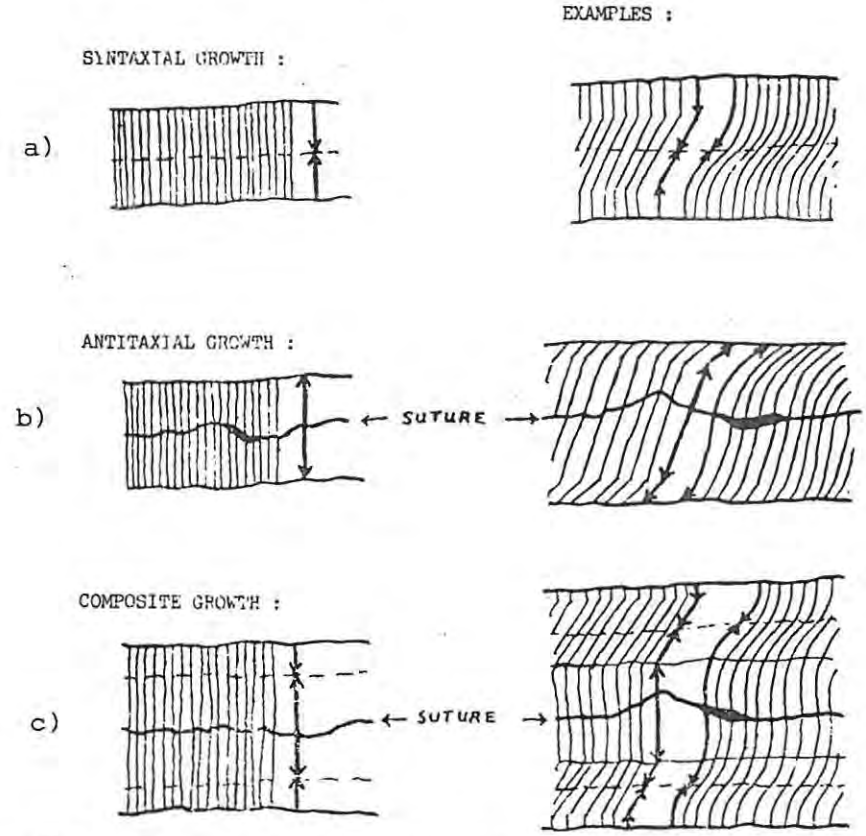


Fig. 2.16 : Schematic chrysotile fibre veins. Simple (a), with a median suture (b), and composite (c). Kinks shorten the milled fibre length. (Laurent, 1975 b).

Laurent (1975b) believes that chrysotile was not derived from unserpentinized olivine remnants but from the dissolution of lizardite. Most of the iron accomodated in the structure of lizardite was expelled to form aggregates of magnetite grains mainly along the vein selvages (Figure 2.15) in the process of the dissolution of the lizardite, its solution transport, and chrysotile fibre growth. One of the commonest characteristics of the asbestos veins is that they are composed of picrolite and asbestos with gradational relationships (Figure 2.17). This characteristic creates problems in the assessment and evaluation of asbestos deposits.

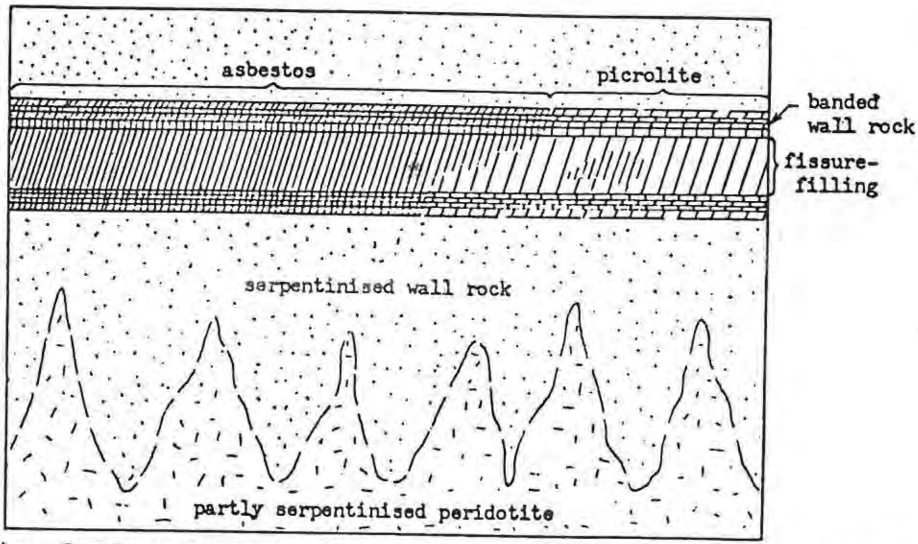


Fig. 2.17: Schematic illustration of amorphous serpentine or picrolite grading into chrysotile fibre (Riordon, 1955).

The asbestos fibre veins are formed as the latest product of the serpentinization process. The host rock provides the vein material as the composition of this material reflects the host rock composition. Riordon (1955) provides examples of harsh, dark green fibre developed in serpentinized ultramafics where the iron content of the host rock is abnormally high, and soft, silky fibre developed where the host rock contains high magnesia and silica and low iron content. This host rock control on fibre composition is confirmed by Nagy and Faust (1956), Frick and Greef (1978), Laubscher (1963, 1964, 1968, 1983a, 1983b) and Büttner (1979). The latter writer showed that fibre development is a function of MgO content and not colour. This host rock control directly affects fibre quality and is an important exploration criterion when determing host rock suitability for fibre development.

Riordon (1955) found that an asbestos fibre tends to occupy a somewhat greater volume than that of an equivalent fibre of picrolite. It is suggested, therefore, that the conversion from picrolite to asbestos would involve an overall increase in volume, and that such a change of stage would be favoured by conditions of tensile strength. Cooke (1937) showed that fibre formation conditions were not the same at the extremities of a deposit and that serpentinization of the vein walls was noticeably less intense. Initial temperatures were insufficient to cause the necessary stress conditions at the margins which prevailed within the main body of the deposit during cooling.

The chief factors favouring the formation of asbestos within ophiolite suites are, therefore, the high temperatures that prevail at the culmination of vein deposition, and the low confining pressures (tensional stress) that existed during the cooling period.

Laubscher (1968, 1980a, 1983b) has summarised the fibre growth mechanism and controlling factors based on the investigation of chrysotile deposits in partially serpentinized dunites, peridotites, serpentinites and dolomites of southern Africa. An understanding of the mechanism and controlling factors is necessary in outlining and evaluating orebodies.

Chrysotile fibre results from three distinct growth mechanisms, ranked in order of descending economic importance: 1) stress-controlled dilation seams; 2) recrystallization of serpentine to fibre; 3) replacement fibre. Stress-controlled dilation seams have formed in existing fractures in which the seam walls and inclusions in the fibre seam can be matched. Fibre growth was only possible if, during growth, the load on the seam wall had been reduced so that the growing force of the fibre was sufficient to move the walls apart. The fibres are orientated at a large angle to the seam wall, regardless of the attitude of the seam, indicating that the walls did not move apart under tension. Laubscher (1963) clearly illustrates that the initiating surface plays an important part in determining the direction of growth. Initially, growth is at right angles to the initiating surface with a change in growth direction when the fibres align themselves in the direction of least resistance. The maximum length of fibre is obtained when the fibres grow in the minimum stress direction. The material for fibre growth was derived either from the fracture wall during serpentinization (example: Shabanie mine), or from solution of the host serpentinite (example: King mine). This mechanism resembles that proposed by Cooke (1937) to explain the origin of the Canadian Quebec deposits.

Recrystallization of serpentine to fibre includes, slip-fibre and certain cross-fibre seams. The slip-fibres are localized in planes of mild shearing, and appropriate trans-planar stress. The serpentine has recrystallized to chrysotile fibre, orientated in the shear direction. The cross-fibre seams are characterized by: fibre grading into the host rock; incipient lenticular fibre seams; parallel fibre orientation independent of seam wall attitude; and fibre development related to minor structures in adjacent seams. Serpentine and picrolite have recrystallized to cross-fibre in areas subjected to constant stress, as at King mine and Sheffield claims.

Replacement fibre is abundant as a result of serpentinization of olivine. The fibre replaces the olivine by growth from crystal boundaries and fractures. Fibre length rarely exceeds 3 mm with direction and length related to the disposition of the initiating surfaces. This mechanism does not give rise to economic fibre seams. Interpretation of the growth mechanism can be influenced by: post-fibre disturbance; contemporaneous plastic deformation of the sidewall serpentine; and original sidewall movement inclined to the observation plane.

Replacement fibre was observed in drill core by the writer (Abbott, 1981) where individual serpentinized annealed olivine crystals were almost completely replaced by fibre. Fibre length was dependent on crystal size as interstitial magnetite prevented fibre growth between crystals, resulting in uneconomic fibre development.

Laubscher (1963) concluded that no fibre growth will take place unless the load on the fracture has been released. Structural control thus plays a very important part in the formation of ore deposits. Fibre growth will continue provided material is made available and a state of tension exists in the host rock. Cooke (1937) also postulated similar fibre growth mechanisms for the Quebec asbestos deposits.

Laubscher (1963) disagrees with Riordon's (1955) proposal that picrolite crystallizes to economic asbestos fibre. Laubscher maintains that this intimate association of picrolite and fibre is not found in economic fibre seams in southern African deposits and is not of economic importance in Precambrian ultramafic complexes. Lamarche and Wicks (1975), and Petrov and Znamensky (1978) agree with Riordon that this fibre genesis is common to asbestos deposits developed within ultramafic ophiolite suites.

The genesis of chrysotile fibre in the Precambrian ultramafic complexes of Canada (Hendry and Conn, 1957; Stewart, 1976; 1978) is remarkably similar to that of southern Africa, as proposed by Hall (1930), van Biljon (1959, 1964) and Laubscher (1963, 1964, 1980a, 1983b).

The genesis of chrysotile fibre is therefore slightly different between the two ultramafic host rock types although the primary structural controlling factor prevails throughout all asbestos deposits.

THE GEOLOGY OF CROCIDOLITE AND AMOSITE ASBESTOS

The iron formation of the Transvaal Supergroup is the world's major producer of asbestiform amphiboles. Most of the production is of crocidolite (blue) asbestos, the fibrous form of the soda amphibole riebeckite. Smaller amounts of amosite (the fibrous polymorph of grunerite) are produced from a localized portion of the Transvaal basin, around Penge in the northeastern Transvaal (Figure 3.1). In the transitional area between the crocidolite and amosite producing regions, alternate layers of the two asbestos varieties are often found juxtaposed. In the Pietersburg region, some seams of asbestos consist of alternating fibres of riebeckite and amosite, and give rise to montasite, the "lavender blue" asbestos (Cilliers, 1964), which is mined locally.

These deposits are found in the Penge, Asbesheuwels, and Koegas Formations of the Transvaal Basin, and have been described by numerous writers(listed on page 21).

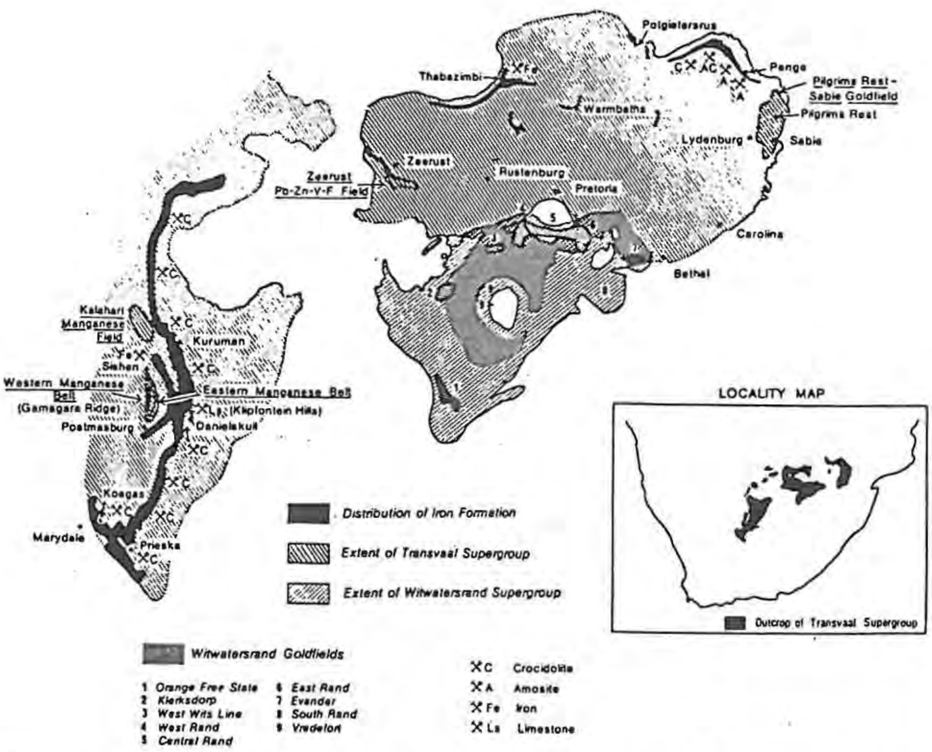


Fig. 3.1: Map showing the distribution of the Witwatersrand and Transvaal basins and their principal stratiform mineral occurrences. Inset map shows outcrop of Transvaal Supergroup in South Africa.
(Anhaeusser and Buttton, 1974)

Crocidolite has been mined over a strike length of 500 km in the northern Cape (Figure 3.1) with fibre developed at five principal levels, four of them in the Asbesheuwels Formation and one in the Koegas Formation. Relatively unimportant amounts of crocidolite are mined in the Penge Formation of the northeastern Transvaal. Mining continues at a high level, with a production of over 118 000 tonnes recorded for 1980 (see Appendix, A5). Crocidolite fibre is valued for its high tensile strength and acid resistant characteristic. It has many uses, the principal one being in the manufacture of asbestos cement products.

Amosite is mined in the Penge Iron Formation in the northeastern Transvaal (Figure 3.1). Fibre production for 1980 was over 57 000 tonnes (see Appendix, A5). Amosite is only commercially exploited in South Africa and is valued for its exceptional fibre length and high bulk volume. The principal use is in the manufacture of fireproof insulation boards.

The Hamersley Basin, Western Australia also contains reserves of crocidolite. It is found in the Marra Mamba, Brockman and Boolgeeda Formations of the Hamersley Group. This asbestos has been described by Miles (1942), Trueman (1963), Finucane (1965), Trendall and Blockley (1970), Blockley (1976) and Button (1976). Mining of crocidolite fibre was essentially restricted to the area south of Wittenoom where units in the Dales Gorge Member of the Brockman Iron Formation were exploited (Button, 1976). Production of crocidolite in Australia has ceased owing to indifferent grades. A total of 155 000 tonnes of fibre has been produced since 1933 (Trendall and Blockley, 1970).

Amosite has not been recorded from the Hamersley Basin. If the analogy with the Transvaal Basin is used, it could conceivably be present in the basin marginal areas, where the Marra Mamba and Brockman iron formations are truncated by the unconformities developed at the base of the Wyloo and Manganese groups (Button, 1976).

A unique amphibole fibre having an anthophyllite habit and the appearance of crocidolite occurs in Bolivia, near Lusaka in Zambia, and in the U.S.S.R. (Hodgson, 1975). This fibre occurs in host rocks of deep-seated magmatic origin and has no association with sedimentary deposits.

Host Rocks

Both crocidolite and amosite asbestos deposits are located within Precambrian metamorphosed sedimentary banded iron formations of ca 2300-2100 Ma age which form extensive stratigraphic units within cratonic domains. In the reconstruction of Gondwanaland of Pre-Jurassic times there is very good stratigraphic correlation of the banded iron formations of the southern continents. Hodgson (1975) traces the probable boundaries of the vast Transvaal epeiric sea of early Gondwanaland times in which the Precambrian iron formations were deposited. The banded iron formations and crocidolite deposits in the Hamersley range of western Australia are almost identical to those in South Africa; the southern Indian amphibole asbestos deposits are in Precambrian ironstones similar to those of the eastern Transvaal and the South American iron formations are similar in lithology and occurrence to those in South Africa and India. It is likely, therefore, that the Precambrian iron formations of Antarctica may also contain amphibole asbestos.

The South African iron formations are developed adjacent to the platform edge of the Transvaal Basin, clearly illustrated in Figure 3.2. The Murchison lineament approximates the basin edge in the vicinity of Penge, resulting in fumerolic and/or exhalative volcanic activity with Na-rich brines locally replacing Fe-silicates in the iron formations of the area. This replacement has caused the lateral gradation of amosite-bearing iron formations into crocidolite-bearing iron formations to the north and west of Penge. The Griquatown and Patrysfontein fault zone in the southwestern portion of this basin is also developed along the platform edge. Similar fumerolic and/or exhalative volcanic activity has caused extensive replacement of Fe-silicates by Na-rich brines, forming riebeckite within the Griquatown and Kuruman Iron Formations, confirmed by Hanekom (1966).

Stilpnomelane and iron silicate-rich zones occurred at cyclic intervals in the banded iron formation, so that the riebeckite developed in specific, stratigraphically controlled zones. The development of the riebeckite zones was controlled by the chemistry of the brines and the host iron formations, with the riebeckite-rich bands forming the potential hosts for structurally controlled crocidolite asbestos mineralization.

The host to the mineralization was conditioned by syngenetic and later diagenetic processes, although the mineralization is directly related to subsequent structural controls. Trendall and Blockley (1970) found that preferential development of crocidolite fibre within specific stratigraphic units also occurred in the Hamersley Range of Western Australia. Hanekom (1966) discovered that crocidolite-rich units are also richer in layers of stilpnomelane, which contain shard structures indicative of a volcanic origin. Volcanism is thought to have occurred in the early phases of the sedimentation cycles, while chemical sedimentation dominated in non-volcanic periods later in the cycles.

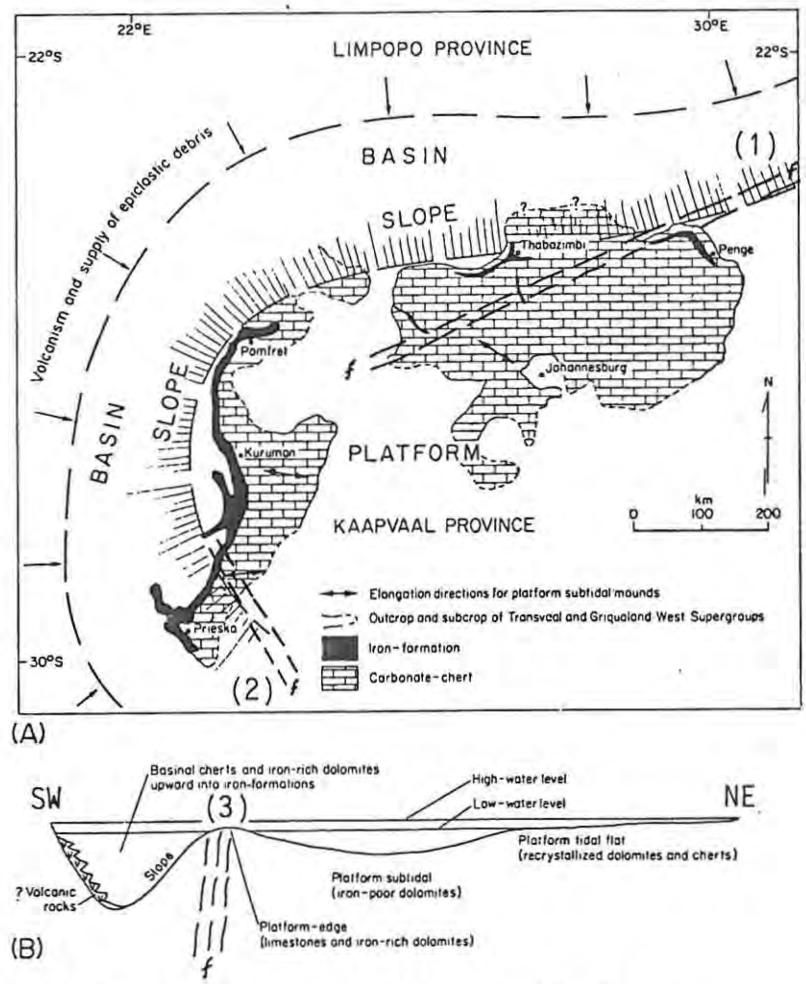


Figure 3.2: (A) Tectonic setting of the Ghaap and Chuniespoort Groups showing the inferred location of the various environments.
(B) Paleoenvironmental reconstruction of the Ghaap and Chuniespoort Groups.

(1) Murchison lineament.
(2) Griquatown & Patrysfontein fault zone.
(3) Fumerolic and exhalative activity along (2) fault zone.

(Modified from Tankard et al.,1982)

Beukes (1978) found that riebeckite is commonly associated with the iron-silicate zones of the basinal, slope and platform facies of the Transvaal Supergroup. He suggests that the sodium may be of fumerolic origin in the basinal and slope environments, but was concentrated by evaporation on the platform.

A great deal has been written (much of it conflicting) on both the origin of riebeckite and on the mechanism of crocidolite fibre development. In summary, South African investigators believed that riebeckite was the diagenetic product of a primary sediment, termed proto-riebeckite. Cilliers and Genis (1964) were of the opinion that this material was an attapulgite-like clay, while Hanekom (1966) regarded it as a volcanic ash. In Australia, Trendall and Blockley (1970) have shown that iron formation and riebeckite were derived from a common precursor sediment. They believe that those parts of the precursor that had been relatively uncompressed were preferred pathways for migrating soda-rich liquids, which metasomatically converted the precursor to riebeckite. The microscopic work of Grubb (1971) suggested that riebeckite formed diagenetically, through sodic metasomatism of stilpnomelane. However, Ayres (1972) showed that riebeckite also formed by metasomatic replacement of quartz-iron oxide mesobands. The presence of riebeckite in the iron formation of the Transvaal Supergroup, and its relative scarcity in other iron formations around the world, is taken by Cilliers and Genis as a measure of the salinity of the waters in the Transvaal depository. The change from the precursor phase to riebeckite is seen as a process involving dehydration and some ionic reorganization. Such changes occurred at low (diagenetic) temperatures.

<u>Crocidolite asbestos</u> mineralization is sporadically developed within the Asbesheuwels Subgroup of the Ghaap Group, from south of Prieska to Pomfret in the north, a strike length of some 500 km (Figure 3.2). The asbestos mineralization is concentrated in the central Postmasburg Kuruman area, where the Asbesheuwels rocks have been refolded into an elongate arcuate syncline. Refolding has created the stratigraphic duplication of the potential asbestos-bearing horizons.

The Kuruman and Griquatown Iron Formations show a progressive change from lower well bedded banded iron formation through fine-clastic iron formation to coarse-clastic and brecciated iron formation. This represents a facies change up the sequence from deep platformal (open shelf) iron formation through platformal and lagoonal iron formation to supratidal iron formation . The iron formations are thought to have been deposited during cold climatic conditions, and Beukes (1978) suggests that the Kuruman Iron Formation was deposited in an open shelf environment, while the Griquatown Iron Formation was deposited in a platform to lagoonal environment.

The Groenwater High coincides with the Griquatown-Patrysfontein fault zone resulting in thicker sedimentation to the southwest, in the Prieska area (Figure 3.2). The Kuruman Iron Formation consists of a sequence of finely banded chert with interbedded iron silicate-rich, iron carbonate-rich and iron oxide-rich bands. Greenalite, grunerite and stilpnomelane are the main iron silicates, and the succession shows a cyclic increase in magnetite and a decrease in stilpnomelane in five major-cyclic units (Figure 3.3). Riebeckite occurs in distinct zones within the iron formation and occurs as massive felted units within this well laminated open shelf iron formation. The Griquatown Iron Formations consist essentially of a clastic iron formation that comprise a series of upward coarsening mega-cycles. The riebeckite occurs as siliceous riebeckite zones and massive riebeckite zones within this clastic iron formation.

The riebeckite is thought to have formed by the diagenetic movement of Na-rich brines through the iron formation. Secondary magnetite is associated with some of the riebeckite zones which represents excess iron that was liberated during the replacement of original Fe-rich aluminosilicates by sodium. The magnetite-rich riebeckite zones are potential hosts for crocidolite asbestos mineralization.

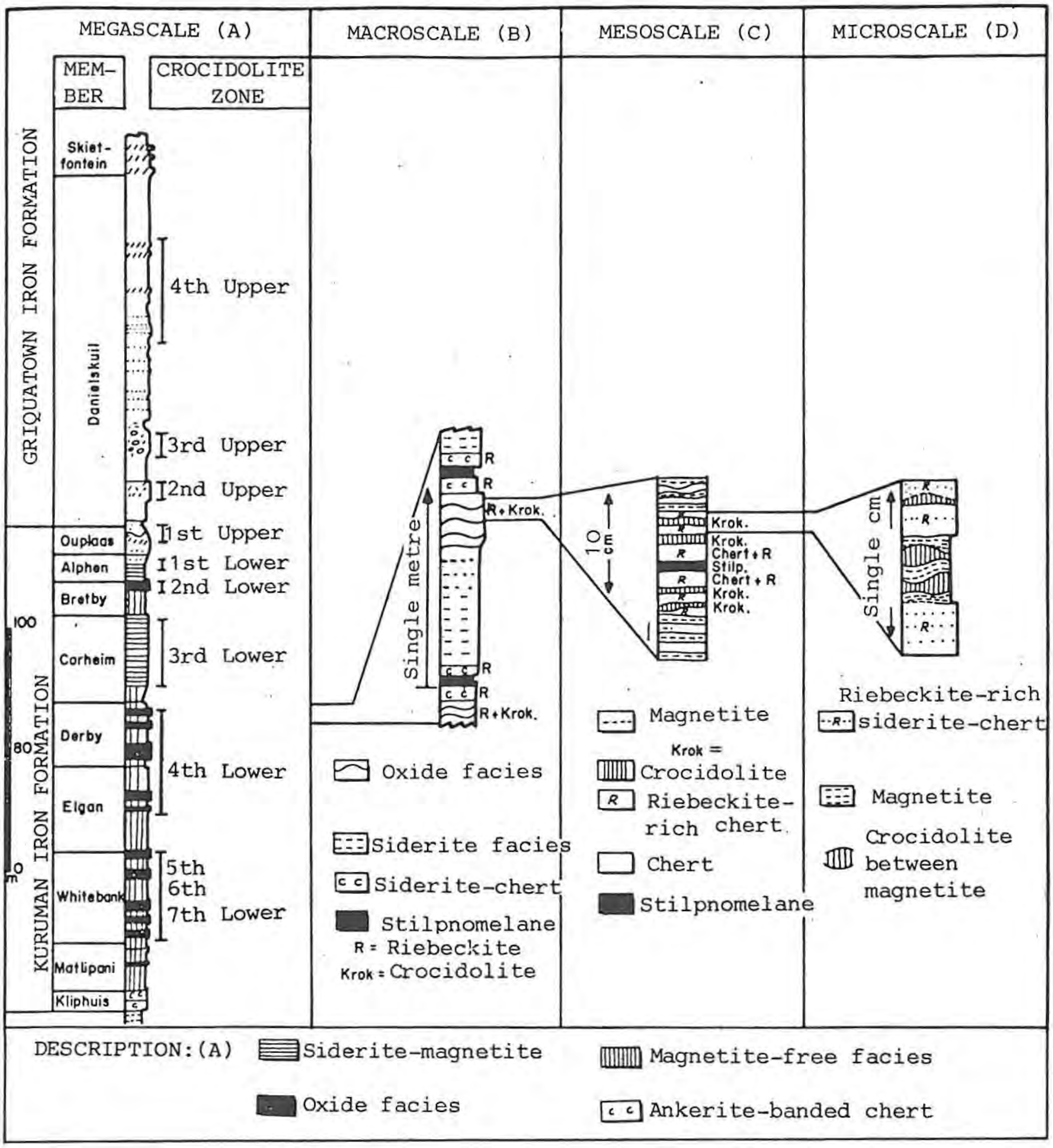


Figure 3.3: Stratigraphic column of the Kuruman and Griquatown Iron Formations in the Asbesheuwels Subgroup showing the development of stratigraphically controlled riebeckite-bearing zones. These riebeckite-bearing zones are potential hosts for structurally controlled crocidolite fibre. The association of the crocidolite with the iron formation on a macro-scale, meso-scale and micro-scale is diagrammatically illustrated. (Modified after Beukes, 1978)

Amosite asbestos is developed within the Penge Iron Formation in the northeastern Transvaal (Figure 3.1) over a strike length of some 35 km. The fibre-bearing units are presently mined at three localities : at Penge, Weltevreden and Kromellenboog mines. The geological setting and mode of occurrence of amosite are similar to those of crocidolite and have been described by Hall (1930), du Toit (1945), Vermaas (1952), Keep (1961), Cilliers (1964), Hodson (1975), Winson (1975), Mann (1981) and reviewed by Button (1976).

The amosite asbestos occurs in banded iron-formation that is underlain by, and in transitional contact with, a thick sequence of dolomite. The upper contact of the iron-formation is marked by an angular disconformity and is overlain by a sequence of quartzites and shales. The iron-formation is composed of alternating light-coloured bands of quartz and chert with some siderite, and dark-coloured bands of magnetite, fine grained, randomly oriented grunerite of the same composition as the asbestos, and graphitic material. Soft, gray to black non-magnetic shales are also present. The bands vary from microscopic thicknesses up to several centimetres, and can be traced laterally for many kilometres. These sediments dip southwestwards at about 20°. The sequence has been intruded by thin persistent sills of dolerite, while diabase dykes vertically intrude the formations at intervals. The Bevets conglomerate is considered an important marker horizon for the fibre-bearing formation. The asbestos occurs as clearly defined lithologic units parallel to the bedding. The fibres occur at right angles to the bedding forming cross-fibre veins, which vary in thickness from a fraction of a millimetre up to 30 centimetres, and vary in length from a metre to 4 metres.

The amosite-bearing iron formation grades laterally to iron formation in which crocidolite predominates, when traced towards the north and west in the northeastern Transvaal. The lateral change from crocidolite - to amosite-bearing iron formation was seen by Cilliers (1964) as a manifestation of paleosalinity in the ancient depository. Genis (1964) thought that the amosite was derived from an attapulgite-like clay, with ferrous cations instead of soda. However, Button (1974) noted that the amosite-bearing iron formation occupies a fairly unique stratigraphic position, in that it sub-outcrops beneath the pre-Pretoria Group unconformity.

It is thought that circulating groundwaters operative during the era of pre-Pretoria weathering may have leached soda from crocidolite, or proto-riebeckite, leaving amosite as the leached product. The lateral change from one asbestos type to the other could be due to proximity to an intraformational weathering surface.

Structural Control

Structural control on the development of crocidolite orebodies is well established in the northwestern Cape (Cilliers and Genis, 1964; Hanekom, 1966; Fockema, 1967). Cilliers (1964) considers the effects of folding to be practically negligible in the Penge area, although faulting has disrupted the ore zones. Hodgson (1975) noted the geological contrast between the crocidolite and amosite deposits of the north-eastern Transvaal. The crocidolite of the Pietersburg Asbestos Field is developed within moderately folded strata in a deeply incised area, while the amosite deposits of the Penge area are uniformly dipping south-westwards.

Whittaker (1979) suggests that the folding of both regions has been a critical element in the development of the asbestos. In the Transvaal deposits, the iron-formation and associated sediments have been folded along two major axes. One, the strongest, trends east-west and a second, weaker set, trends north-south. The interference of the two sets of folds forms a series of large basin and dome structures. The asbestos deposits occur associated with these cross-fold structures. In the northern Cape, a large, gently-dipping synclinal fold, the Dimoten Syncline, with a north-south axial trace, has been folded on both its east and west limbs into a series of monoclines. The asbestos deposits are located in these monoclinal and basin structures (Dreyer and Robinson, 1978). These observations suggest that although chemical and bio-chemical sediments are essential host rocks, the formation of crocidolite and amosite asbestos can only take place in a favourable stress environment. However, the control by deformational processes on crocidolite development is a controversial subject. In the northern Cape, an early, fairly open phase and a later, more intense phase of deformation has been recognized.

Some investigators (Cilliers and Genis, 1964) contend that only the early phase of folding affected fibre development, while others (Hanekom, 1966; Fockema, 1967) are of the opinion that both phases of deformation are important. The evidence presented by Hanekom points conclusively to the latter view, at least in portions of the northern Cape asbestos field. It would appear that the proto-amphibole "flowed" towards the axes of folds, where it crystallized into crocidolite. Exploitable deposits of crocidolite are thus frequently stacked one above the other in the axial zones of folds, in a style reminiscent of "saddle reefs". The structural control on the economic development of fibre has been used in exploration, where detailed structural studies have resulted in the discovery of non-exposed ore bodies (Anhaeusser and Button, 1974).

Dreyer and Robinson (1978) established that the crocidolite asbestos mineralization is structurally controlled within specific riebeckite-rich stratigraphic zones. Crocidolite asbestos is a structurally reorientated form of riebeckite, with the asbestos developing from massive riebeckite bands within the iron formation in regions under tensional stress. The mineralization occurs as cross-fibre seams developed in tension partings along bedding planes. The asbestos fibres grade laterally into riebeckite and appear to have formed from the latter by the diagenetic addition of Na and loss of CO_2. Characteristically the top and bottom contacts of the seams are bounded by thin layers of magnetite, along which the host rock has tended to preferentially part during local deformation to form open space sites. The stratigraphy is affected by gentle flexures, which occasionally cause local drag folds and restricted, intraformational disharmonic slumping in the iron formations. These disharmonic folds are often isoclinal, but generally tend to be of limited vertical profile, fading out within a few metres. Amplification of these partings in intraformational fold closures commonly produces a corresponding increase in the fibre length. Folding generally tends to enrich the mineralization, but in certain areas late stage deformation may result in the destruction of fibre, or in the reduction of fibre length, by kinking. The orebodies tend to be oval in shape with the long axis trending either east or west of north (Figure 3.4), which correspond to the regional interference fold pattern affecting the host rocks.

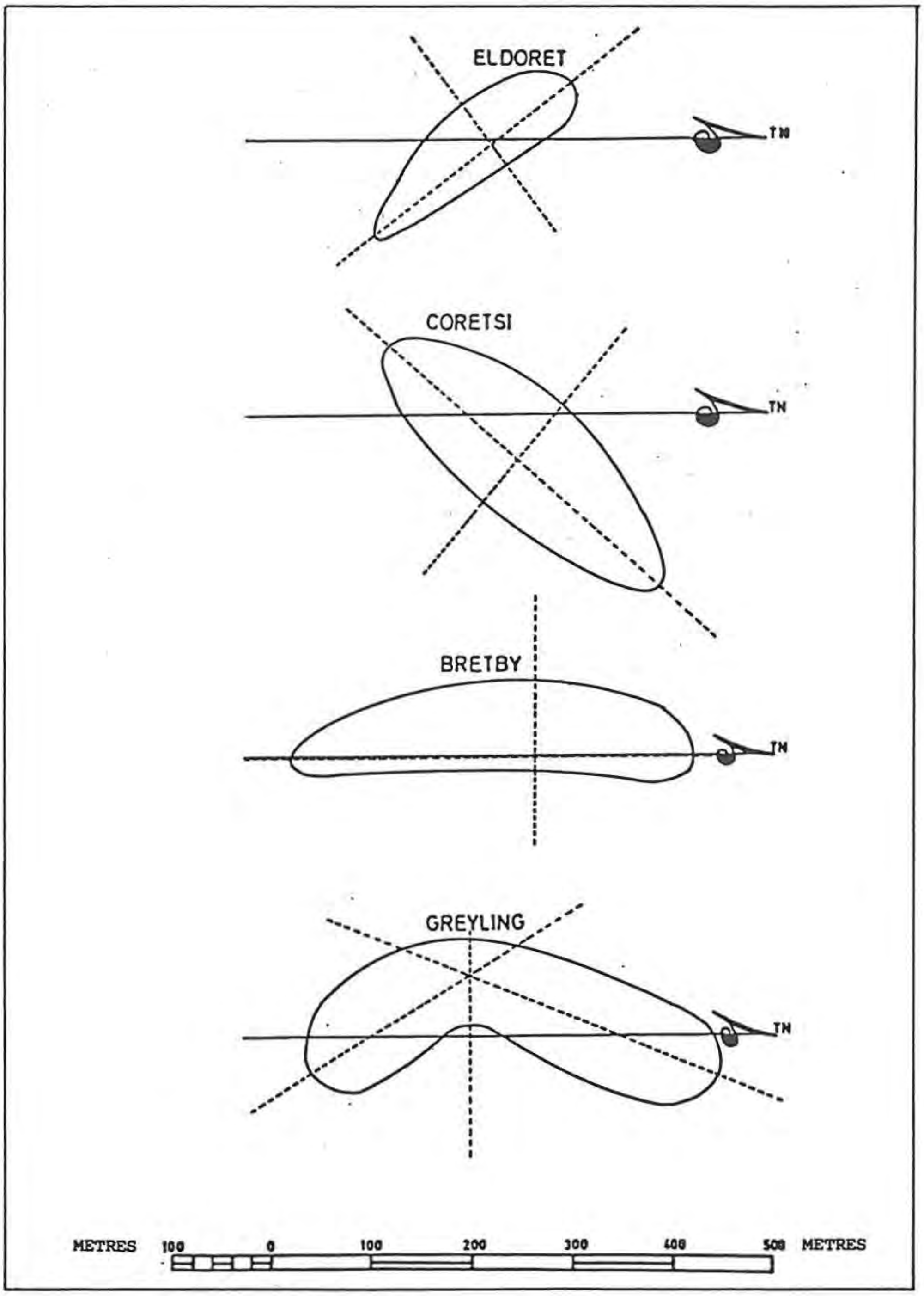


Figure 3.4: Size, shape and orientation of some crocidolite asbestos orebodies. Regional interference fold patterns control their orientation.
(Gefco geology dept., Kuruman, 1982)

The average size of an orebody is approximately 300 m x 500 m, with the individual reefs seldom exceeding 4 metres in width. The lateral fringes of the orebodies are delineated by a marked thinning of the asbestos fibre seams to below economic lengths, while the stratigraphic thickness of the hosting rock units remains relatively constant. The lower asbestos-bearing reefs tend to become progressively narrower and have less lateral extension, thereby giving the impression of being located within a local depression that could be either a primary depositional basin or structurally controlled synform (Figure 3.5). However, from the descriptions and distributions of the occurrences it appears as though the deposits are intimately related to synclinal and occasional anticlinal structural flexures.

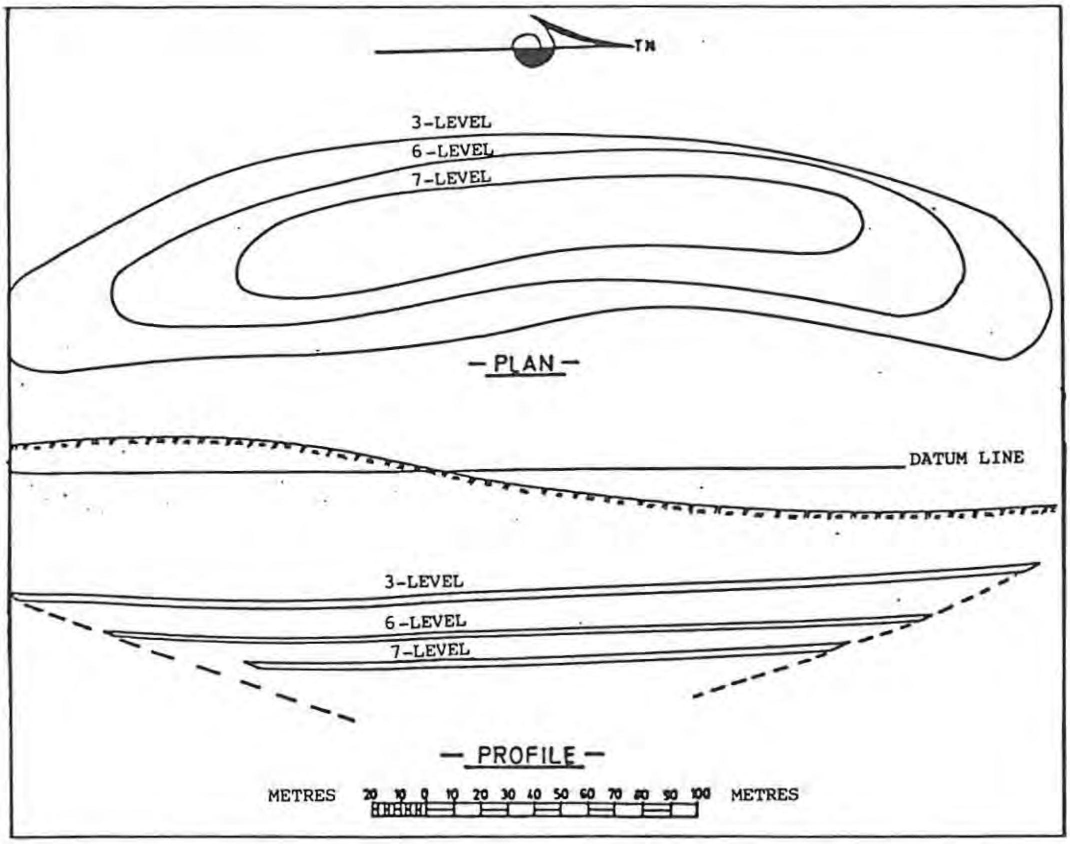


Figure 3.5: Horizontal and vertical distribution of fibre zones, illustrating their narrowing in depth, from the Bretby mine, Ouplaas Member. (Gefco geological dept., Kuruman, 1982)

The orebodies tend to occur in swarms, an example of which is located at Coretsi-Eldoret, north of Kuruman, where nine orebodies of varying size occur within a 5 km radius. This suggests that there are preferential areas within which orebodies have developed. Orebodies are developed in clusters throughout the northern Cape crocidolite field, localized by the regional interference fold pattern (Gefco geological staff, pers. comm., 1982). In the Coretsi area the orebodies tend to occur only on one limb of the synform while in the Kuruman area they tend to occupy the whole synform, caused by refolding and duplication of the potential ore horizons.

The oval shaped, downward tapering synformal orebodies suggest that localized pods of Na-rich brines were operative within the basin which conditioned the host rocks for later fibre development. Further evidence is that riebeckite bands grade laterally into siderite-ankerite bands outside the ore zone. Vertically, riebeckite is superceded by siderite and greenalite facies, then a siderite-magnetite facies, capped by a magnetite-rich facies which includes riebeckite and crocidolite, the ore horizon. Abundant stilpnomelane layers occur within the succession and are often replaced by riebeckite in the ore zone. Grubb (1971) recognized that riebeckite and crocidolite are the end products of stilpnomelane diagenesis.

Crocidolite fibre occurs in the hinge zones and on the limbs of the small scale basin and dome structures, clearly illustrated in Figure 3.6. The surface area decreases as the fold dies out, resulting in a reduction in fibre grade, while the crocidolite is orientated at about normal to the bedding surface. Fibre is irregularly distributed but generally the higher grades are associated with fold axes. Very small scale "cone-in-cone" structures cause the fibre length to vary markedly on a local scale, reflecting very small scale basin and dome structures within some bands.

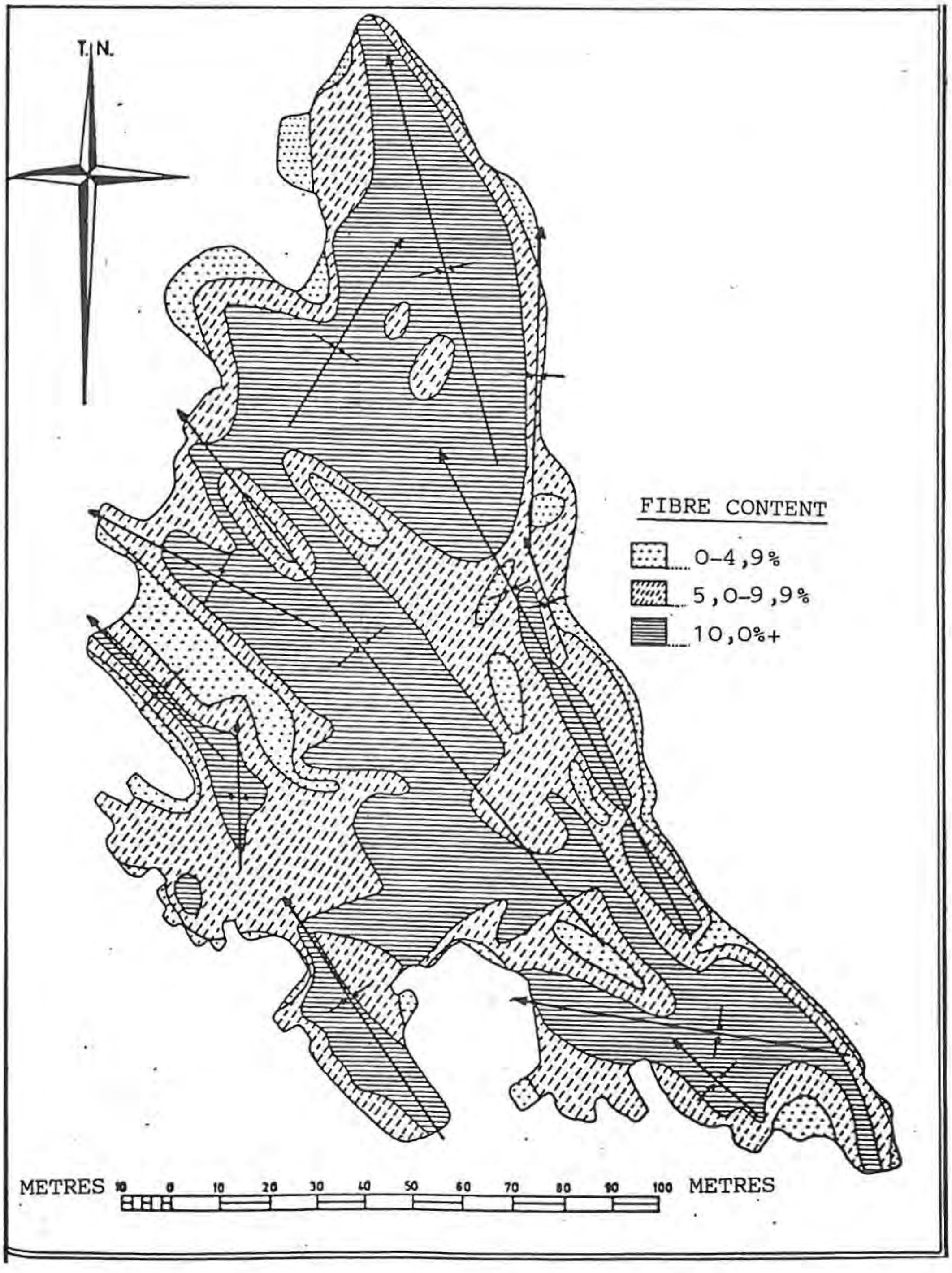


Figure 3.6: Irregular distribution of fibre grade associated with folding in a stratigraphically controlled ore zone at Strelley mine.
(Gefco geological dept., Kuruman, 1982)

Fibre Veins

Crocidolite asbestos is an aligned fibrous form of reibeckite, while amosite is the aligned fibrous form of grunerite.

Cross fibre veins are the main form of ore in both types of deposits. These veins are found as closely spaced ribbon fibre roughly conformable with the bedding which locally is distorted and steeply dipping. Fibre length often increases in the axes of disharmonic folds although post-fibre deformation creates kinked fibre which reduces the effective length of the fibre. Individual fibre bands often contain natural partings which also reduces fibre length.

Slip-fibre veins have been formed due to shearing and faulting after the development of the cross-fibre veins but do not form a significant source of ore. Magnetite is the main accessory mineral associated with both types of asbestos. It occurs as euhedral or subhedral grains at the margins of veins, in the partings of veins, or inter-grown with the fibres. It tends to be more abundant with amosite asbestos, but both types may also be free of magnetite. Near surface weathering and oxidation may produce limonitic stains on the asbestos fibres. Another common impurity found in refined asbestos is fine grunerite or riebeckite dust produced by the crushing of the dense and tough host rock.

The most important quality parameters of crocidolite asbestos are the fibre length, tensile strength and fibrility. The fibre length is the main parameter that determines the grade of the mineralization. The fibre length varies between 50 mm and less than 1 mm. Fibre lengths less than 3 mm are considered uneconomic. The average fibre length found in the economically mineralized reefs averages approximately 8 mm. Gangue minerals in the reef consist of chert, carbonate (siderite), greenalite, riebeckite, stilpnomelane, magnetite and chlorite.

Amosite veins are noted for the fibre length, which often ranges up to 30 cm. The tensile strength of this fibre is not as high as that of crocidolite.

Fibre Genesis

Several controlling factors are required for fibre growth: the host rocks must be preconditioned by replacement so that they contain riebeckite- or grunerite-bearing horizons; and deformation of the host rocks, caused by intraformational competency contrasts or brecciation, creates permeable dilation sites or low-stress environments for the migration of sodic brines.

Investigators in both the Transvaal and Hamersley basins have documented the growth of riebeckite needles around magnetite (Cilliers and Genis, 1964; Grubb, 1971; Ayres, 1972), which may have acted as the initiating surface for fibre growth. Cilliers and Genis (1964) and Genis (1964) believed that crocidolite fibres formed in a band of proto-riebeckite, adjacent to a layer of magnetite. The magnetite crystals provided a constant number of growth-points per unit area, a feature essential to the orientation of fibre. In layers of proto-riebeckite where magnetite is absent, this material was thought to have crystallized to an assemblage of disorientated riebeckite needles, known locally as mass-fibre.

Their work has been superseded by that of Hanekom (1966), Fockema (1967), Dreyer (1974) and several Australian investigators. Trendall and Blockley (1970) have shown that crocidolite grew in dilatant sites formed as a response to two opposing stresses. Fibre growth is thought to have been within magnetite layers, the chemical constituents being derived from the adjacent iron formation. Grubb (1971) stressed that crocidolite was preferentially developed in intraformational breccias, which are inferred to have been more permeable to migrating sodic brines than the surrounding iron formation.

Dreyer (1974) discovered that most amosite fibre seams do not contain associated layers or bands of magnetite and that amosite is found in the soft "amosite" slates, which are entirely non-magnetic. He concluded that a proto-amphibole solution was initially essential prior to recrystallization into fibre in favourable low-stress environments. The fibre type so formed depended upon the exact composition of the original parent material : the sodium rich proto-amphibole produced crocidolite while the magnesium rich proto-amphibole created amosite and anthophyllite. He suggested that, since amosite required more iron for its formation than crocidolite, most of the iron present in the solution was used up in the formation of this fibre. The crocidolite, however, not requiring all of the iron, expelled it as a residue which crystallized out as irregular bands of magnetite at the contacts of the fibre and sidewalls. Hanekom (1966), Dimroth and Chauvel (1973) and Klein (1974) confirmed that magnetite was formed as a low temperature metamorphic mineral and crystallized at the same time, or later than, the riebeckite.

Certain stratigraphic units were transformed into asbestos fibre only in localized areas, with extensive, apparently barren, areas inbetween them. The barren areas show no detectable mineralogical difference from the units in which the fibre developed. Fibre only developed in basin and dome areas where these units coincided with intersecting regional cross folds. The sizes of the structurally suitable areas are entirely dependent on the size, shape and intensity of the interference folds.

It is likely that the magnetite layers, associated with the fibre, preferentially parted during local deformation due to intraformational ductility contrasts, creating open space sites. This enabled remobilized riebeckite or Na-rich brines to migrate to these low-pressure areas where the crocidolite fibre recrystallized, using the magnetite or other sidewall material as the initiating surfaces for fibre growth.

The fibre grew in the direction of least resistance, parallel to the minimum stress direction, about normal to the stratigraphic layering. Orientation of the fibre is thus unlikely to have been due to the influence or presence of the magnetite but due to the low-stress environment. Unorientated mass fibre, formed without magnetite, is likely to have recrystallized in less favourable stress environments which did not allow fibre to recrystallize only in one direction. The absence of magnetite also suggests that the dilation sites were not fully developed during deformation.

EXPLORATION FOR ASBESTOS

Geological mapping is of prime importance in locating favourable rock types and structural sites for asbestos development. However, other methods are also important especially in poor outcrop areas. Serpentinization usually produces secondary magnetite so that airborne and ground magnetic surveys can delineate ultramafic rocks (Low, 1951; Conn, 1957; 1969). Serpentinization does not always produce secondary magnetite, but in some cases an iron-bearing brucite is formed instead. These serpentinites will have little magnetic expression but may, nevertheless, be potential asbestos hosts.

Geochemical surveys in conjunction with geophysical methods have been used to delineate unexposed ultramafic bodies (Abbott, 1978). It was found that nickel soil anomalies (total extraction) invariably coincided with high ground magnetometer readings (over 1000 gammas). The latter anomalies were, however, much narrower than the former which indicated that the magnetic method delineated the actual size of the concealed ultramafic body. The geochemical anomalies were probably much more extensive due to soil creep and sheetwash, especially where the topography was steep.

In Canada, owing to a lack of outcrop within areas of ultrabasic rocks, or within a belt in which these rocks are expected to occur, both aeromagnetic and ground magnetic surveys are often employed in the early stages of asbestos exploration. Conn (1969) showed that ground magnetic surveys are used to check and define in more detail those anomalies obtained by an airborne survey of a large area, or the ground survey alone may be used for exploring a small area.

Both ophiolite complexes and Precambrian layered ultramafic complexes were examined by Conn who found that magnetic surveys could also segregate the layers in a composite layered complex, which is of prime importance in southern African asbestos exploration. Cross-faulting produces complex magnetic contour patterns, while overburden thickness creates interpretation problems. Shallow seismic surveys have been successfully used to determine the actual overburden thickness, which has improved interpretation of the magnetic patterns.

The Advocate mine, Newfoundland, was magnetically surveyed. The magnetic contour pattern and intensity clearly distinguishes the moderately to highly serpentinized zones of the main ultrabasic body (Figure 4.1). Known asbestos orebodies are located exclusively within these zones. However, all such zones do not contain fibre.

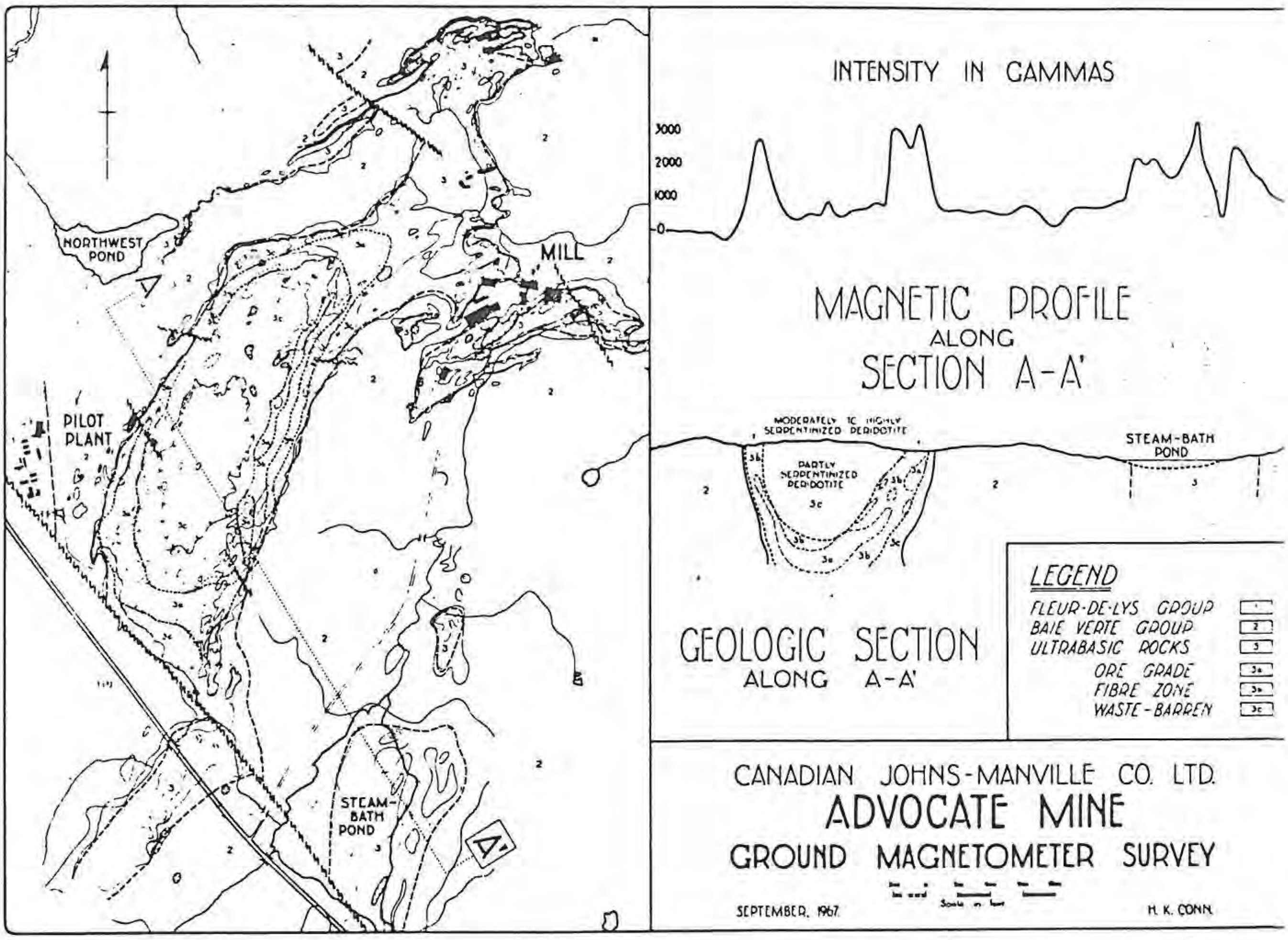


Figure 4.1: Advocate mine, geologic map and ground magnetic profile clearly illustrating the moderately to highly serpentinized peridotite. Asbestos orebodies are located exclusively within these rocks. (Conn, 1969)

The Reeves ultrabasic layered complex boundaries were well defined in a ground magnetic survey with magnetic peaks over the serpentinized peridotite-dunite ore zone clearly illustrated in profile A-A' (Figure 4.2). Conn, however, gives no satisfactory explanation for the magnetic anomaly in the southern portion of this mine area. It is of similar intensity to the northeastern anomaly developed over the ore zone but it does not contain fibre.

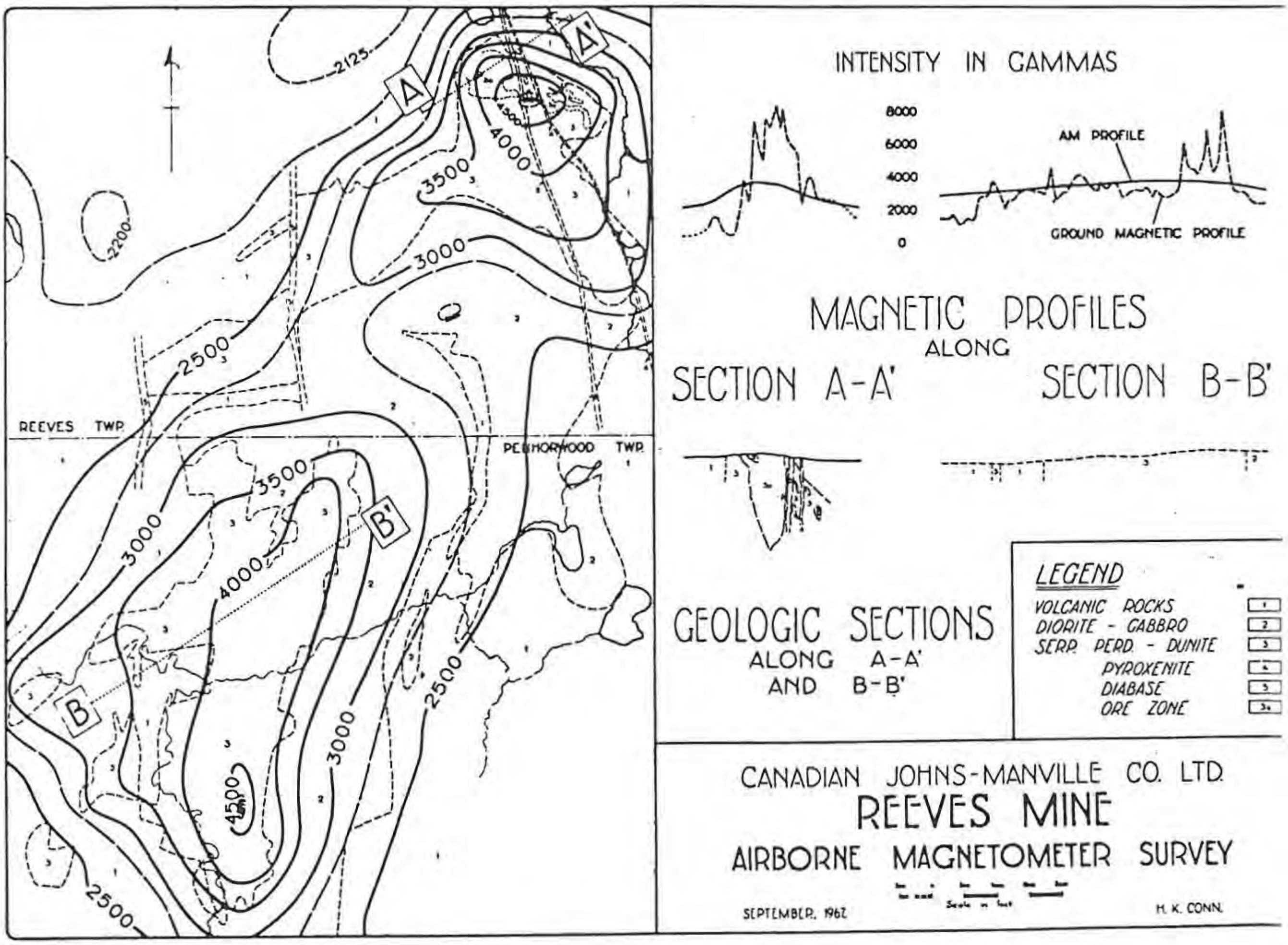


Figure 4.2: Reeves mine, with airborne magnetic map, air magnetic and ground magnetic profiles and sections through the layered ultramafic complex. (Conn, 1969)

Although the magnetic method locates favourable highly serpentinized target areas within ultramafic rocks it does not define fibre zones within the host rocks. These target areas must all be evaluated during exploration.

Lamarche and Wicks (1975) have described exploration criteria for southern Quebec and have summarized the eight common features of the Eastern Townships deposits, including the secondary textures unique to asbestos deposits:

1. The host rock consists of partly serpentinized peridotite (harzburgite variety) or, exceptionally, of partly serpentinized dunite.

2. The magnetite content of the ultramafic rocks seems to increase with their degree of serpentinization.

3. They occur in bodies of ultramafic rocks that have undergone intense compressive and tensional deformation, as testified respectively by shearing and fracturing or veining.

4. They are located right along or near the northwest fault-contact separating the ultramafic rocks from the older and tectonically more stable metasedimentary rocks on the side of the craton.

5. Marked irregularities in the attitude of this contact or in the thickness of the host rock unit are noted near most asbestos deposits.

6. Wherever it can be measured, the dip of this fault-contact near asbestos deposits is found to be steep to the southeast or gentle to the north.

7. Abundant granitic masses are found in most asbestos deposits occurring in the ophiolitic ultramafites.

8. Various typical assemblages of serpentine minerals are associated with most asbestos-bearing ultramafics.

The recognition of this unique assemblage of chrysotile asbestos-type secondary textures could be of importance in the exploration for asbestos deposits, since it presents a further criterion for evaluating promising deposits and could form a basis for determining exploration programmes (Wicks and Whittaker, 1977).

Specimens from about 20 chrysotile asbestos deposits - Eastern Townships, Quebec; northern Quebec; Ontario; Manitoba; British Columbia; California; Zimbabwe; and South Africa - have been examined and all display a similar development of secondary textures (Wicks, 1971). The Manitoba Ultramafic Nickel Belt serpentinites were examined by Wicks (1971) and Wicks and Whittaker (1977) to establish the relevance of secondary textures in the exploration for chrysotile asbestos. The intrusions at the southwestern end of the belt, the Little Clarke Lake and Bucks Lake serpentinized ultramafic bodies, are composed of lizardite mesh textures. However, 15 to 25 km towards the northeast, at Bowden and Setting Lakes, secondary non-pseudomorphic lizardite interlocking textures associated with lizardite interlocking veins have developed. A further 30 to 50 km to the northeast, lizardite hourglass textures occur at Joey Lake. A further 8 km northeast, at Pipe Lake nickel mine, lizardite mesh and hourglass textures have been recrystallized to chrysotile-lizardite interlocking textures and chrysotile-lizardite mesh textures. Chrysotile asbestos veins are abundant and antigorite interpenetrating textures are also present. This mine is a nickel mine, not an asbestos mine, but these textural studies indicate that conditions for the formation of chrysotile asbestos become increasingly favourable from the southwest towards the northeast.

Rodingites comprise a wide range of calcium-rich minerals (hydrogrossularite, hibschite, vesuvianite, diopside, nephrite, prehnite and zoisite) that are associated with dyke or sill-like bodies within serpentinized ultramafic rocks. These ultramafics frequently form part of an Alpine-type ophiolite complex or an ultramafic igneous complex in which dunites, harzburgites, pyroxenites and gabbros are generally present. Calcium metasomatism, related to serpentinization of the ultramafic rocks, has lead to their development (Anhaeusser, 1979). Evans (1977) concludes that temperatures and pressures at which rodingitization occurred are probably very low. The significance of rodingite in metamorphism suggests that its formation is exclusively related to the lizardite-chrysotile type of serpentinization with which chrysotile asbestos formation is associated. The presence of rodingite dykes and sills have been recognised at several South African chrysotile asbestos mines, including African Chrysotile Mines, Msauli (Voigt et al., 1980), Havelock asbestos mines, Swaziland (Barton and van Eeden, 1980; Barton, in press) and the Stolzburg ultramafic complex, Barberton greenstone belt (Anhaeusser, 1979). The gabbro components of the Sheffield and Shabani ultramafic complexes in Zimbabwe contain calcium-rich zoisite and actinolite felspar minerals suggesting that rodingite-type rocks are formed adjacent to chrysotile asbestos deposits within these complexes (Laubscher, 1964). Rodingite dykes are commonly found in the chrysotile asbestos bearing ultramafic rocks of the Eastern Townships of Quebec (Riordon, 1957a; 1975; De, 1967; 1968; 1972), at the Woodsreef mine, Barraba, New South Wales (Benson, 1914; MacNevin, 1976; Glen and Butt, 1981) and at the Krasnouralky mine, Bazhenovo district, central Urals, U.S.S.R. (Arshinov and Merenkov, 1930). The development and recognition of rodingite rocks within a serpentinized ultramafic body is thus an additional exploration criterion for chrysotile asbestos.

Vedernikov (1980) has summarized the exploration criteria for asbestos deposits developed in tectonic domains and concludes that the detection of a large asbestos province requires the identification of the following structures of one of the geosynclinal stages of evolution : basement complex (anthophyllite asbestos); geosynclinal stage (chrysotile asbestos); orogenic stage (amphibole asbestos). He suggests that the exploration region should be subdivided into belt areas, ultramafic massifs and eugeosynclinal areas according to their tectonic positions, in order to locate target areas. Only the ultrabasic belts of the orogenic formations within the fold system are favourable target areas for economic chrysotile asbestos deposits. These target areas should be located near major deep faults, which divide the basement complexes, and on the platform margins.

Diamond drilling is used to further evaluate a prospect. Winson (1975), Laubscher (1980a) and Mann (1981) provide details and Stewart (1976, 1978) gives an interesting account of the problem of drilling in permafrost.

Diamond drilling is normally employed to probe beneath the overburden to assess and define the limits of an asbestos deposit. As asbestos orebodies are usually large in volume it is customary to drill vertical holes on a grid pattern. In the initial stages of exploration an interval of 100 m and sometimes more may be used, filling in to an interval of 30 m or even less, where an asbestos-bearing zone is encountered. In cases where a deposit is elongated in one direction, holes are generally spaced at closer intervals across the strike. Narrow, tabular targets are best explored by angle holes planned to give the attitude and true thickness of the body. Care should be exercised to test the area with one or two preliminary drill holes to determine whether the fibre has a preferential vein angle or not. If the angles of the vein intersections appear random, no changes need be made to the programme. If, on the other hand, the deposit exhibits prominent vein angles which diverge from the average 45°, then the attitude of all later drill holes should be changed to correct for this variation.

Laubscher (1980a) provides details of some drilling techniques used in southern African exploration:

Churn drilling is not extensively used for valueing chrysotile asbestos, but has been successful in the Northern Cape, RSA, crocidolite fields. Cuttings of the rock (fibre intersection) and opened fibre are bailed out of the hole at regular intervals, which in rich fibre development is 150 mm. Fibre content is determined by washing the fibre from the heavy banded ironstone gangue.

Percussion drilling with down-the-hole hammers has been used in the crocidolite fields and also in the weathered zone of chrysotile asbestos where core recovery is unreliable. The fibre is recovered as a cyclone underflow of the dust-collecting apparatus, graded and cleaned in a sample plant, and related to the calculated weight of the ground drilled out. Whilst percussion drilling can lead to fibre shortening, the result obtained will be conservative.

Core drilling is used extensively to locate and value asbestos deposits. In some quarters, diamond drilling has been quoted as inaccurate and has led to mining promotion failures. Analysis of such cases shows that required procedures have been ignored.

Valuation by diamond drilling can be divided into three phases:

(a) borehole siting to ensure good orebody sampling and the optimum angle of intersection with the fibre seams;

(b) selection of optimum core size; for example, for a given fibre length the core size in a stockwork must be greater than in parallel seams;

(c) the right drilling technology for maximum core recovery determined by conscientious core and hole depth measurements; face discharge M series bits are used, BXM being the minimum.

In the past, drill evaluation programmes frequently used small diameter, AX (30 mm) or EX (21,5 mm), core sizes for evaluating any deposits where shearing was minimal and where holes did not exceed 100 m. Experience has shown, however, that large core sizes such as NX (54,5 mm) or BX (43 mm), are preferable for better depth penetration, more geologic data, and to aid in fibre logging and dry milling of the core. The NX core size has been used very successfully in the Zimbabwean, Swaziland and Kaapsehoop (eastern Transvaal) deposits, especially in obtaining geotechnical evaluation parameters essential for these mining operations (Laubscher, D.H., pers. comm., 1981). It was also found that this size provides a more reliable sample for fibre evaluation.

Wire-line drill equipment and the use of non-rotating core barrels are also recommended to mimimize fibre loss by grinding of the core during drilling. Steps are taken to recover the sludge only where core recovery is poor, which is generally the case with slip fibre occurrences. Because of the tendency of the fibre to fluff up and remain in suspension, much greater settling tank capacity is required than is the case when recovering sludge from other minerals. Care must also be taken to avoid contamination by grease and vegetable matter as these cannot be burned off without damaging the fibre. In areas where drilling is impractical, exposure by trenching or exploration beneath the surface by adit or shaft and lateral workings may offer the only means of assessing a deposit.

The following procedure for orebody delineation clarifies mine planning:

Exploratory Outline: Plans and sections, classed as "Exploratory

Outline", will indicate a conservative orebody outline and the location of peripheral features. This information will have been obtained from widely-spaced holes, which will be useful for (a) laying out more detailed exploratory work; (b) initial thinking on mining sequence and methods; (c) long-term planning; and (d) defining the vertical and horizontal limits of areas requiring more detailed investigation.

Planning Outline: Plans and sections will be based on sufficient data so that the magnitude, shape, value and specifications of the orebody and peripheral rocks will not alter appreciably. They must all show structural features and geomechanics classification data which may affect the Mining Layout.

Final Outline: The "Final Outline" stage is reached when all contacts of consequence are shown as a full line, and the geomechanics classification of the orebody and peripheral rocks has been completed.

Thus the evaluation of a new deposit would be undertaken in various stages. If the body outcropped, large samples would be readily available, and the amount and grading of the asbestos ascertained. The extent of the orebody could then be determined by magnetometer surveys, diamond drilling, etc., which would indicate approximately the amount and the asbestos content of the ore. Should these be favourable large diameter drill holes, pilot shafts and development could provide bulk samples which would confirm that the grade of asbestos likely to be produced was consistent and suitable.

Chrysotile asbestos exploration in southern Africa should be concentrated on the ultramafic host rocks within which fibre is likely to occur. Chrysotile asbestos mineralization occurs within serpentinized dunites and harzburgites in layered and differentiated sills that have been structurally deformed. The extent of deformation and tensional stress conditions within the magnesium-rich ultramafics influences the development of cross fibre, controlling length and amount of fibre within the host rock. The host rocks should be sufficiently serpentinized depending on the availability of hydrothermal solutions which are often generated by adjacent intrusives. This alteration provides excess magnesium and silica to form the essential serpentinous solutions which, under favourable conditions, recrystallize into fibre. The greater the amount of solution generated the greater the chance of abundant fibre development.

Liberation of magnetite during serpentinization allows magnetic methods to be used to outline potential host rocks. Geochemical methods can also outline these potential hosts by assaying for Ni and Cr (total extraction). The extent of mineralization cannot, however, be determined by these methods. Structural mapping and core drilling are the most important exploration tools. Careful mapping of fibre vein orientations often provides valuable information for this core drilling.

Asbestos tends to become brittle during weathering so that samples from weathered serpentinites are not representative of the tensile strength of the fibre. Surface fibre does, however, provide good indications of the fibre length developed within the host rock and therefore its fibre potential in depth.

Crocidolite asbestos exploration is concentrated in the western extremity of the Griqualand West Supergroup basin at the platform edge adjacent to the westward deepening of the basin (Figure 3.2). This belt is possibly related to basin edge tectonics, including the Griquatown-Patrysfontein fault zone.

The asbestos fibre is limited to the iron formations of the Asbesheuwels Subgroup occurring in sediments anomalously rich in sodium. Riebeckite- and stilpnomelane-bearing horizons are prime target areas.

The potential ore zones are laterally continuous, stratabound and stratigraphically controlled. The recognition of the various local and regional marker horizons, especially in drill core, is therefore critical.

Structural control is essential with fibre associated with gentle folds, domes or basin structure. Orebodies tend to occur in the axes, or on the limbs, of open synformal structures. Very minor flexures of only 2-3° are sought for suitable target areas. Careful and detailed aerial photographic interpretation of these undulations have been successful in locating orebodies (Wilson, J.G., pers. comm., 1982). Within an orebody zones of intense flexural slip and disharmonic folding are sought as these are the loci for better fibre development.

Most of the known orebodies occur in such folded environments and are oval in shape with the long axis generally striking about north. The ore horizons are usually stacked one above the other and the folding is more intense lower in the succession.

Orebodies tend to occur in clusters so that if one orebody is located there is a good chance of finding others within a 5 km radius, and thus exploration can be concentrated in the vicinity.

Beukes (1978) suggested that a detailed geochemical research programme should be conducted over known deposits to ascertain what variations in Na, Fe^{2+}, Fe^{3+}, Ca and CO_2 occur with distance away from the orebodies. These elements should occur in characteristic haloes around each deposit and this would be very useful in exploration drilling.

Exploration for these deposits is at present confined to those portions of the succession containing known mineralization that outcrop at surface. This entails the diamond drilling of structurally identified potential areas in the correct stratigraphy. However, the flat dip of the strata means that most of the orebodies are blind. Structural contour maps of the recognizable marker horizons from borehole information can be used to predict areas of dome and basin folding, which are the host structures of the ore zones.

When drilling it must be borne in mind that the vertical depth of weathering in this region is about 60 m, and fibre from the weathered zone is unsuitable. Thus the stratigraphic position is critical when drilling for fibre zones, as allowance must be made for this depth of weathering. No techniques have been developed for exploring beyond the limits of known mineralized horizons, and thus future problems can be expected when exploration moves northwards into the extensive sand-covered areas. It is therefore essential to understand the fundamental factors controlling the location of these deposits to generate further exploration target areas.

Amosite asbestos exploration is adequately described by Wilson (1975) and Mann (1981). With the steady depletion of known amosite ore reserves, extensive exploration for additional ore was initiated a few years ago. Considerable success was achieved by utilizing a novel structural approach developed by the Cape Asbestos Group.

The Bevets conglomerate is an important marker horizon which occurs immediately above the main fibre zone and marks the position of a distinct disconformity. Careful mapping of this horizon with respect to detailed topographic contours disclosed a system of broad, gentle north-south folds having amplitudes of about 15 m and wavelengths of 1200 to 1500 m between crests. A second, superimposed pattern of east-west cross folds was also detected having similar amplitude and a wavelength approaching 2000 m. Careful structural mapping further indicated that each of the known or producing deposits was located on the loci of intersections of either anticlinal or synclinal structures. Consequently, by drilling similar loci, at least five new fibre occurrences were discovered and the sixth failed only because the precipitous terrain in the area prevented drilling directly on target. Nevertheless, a drill hole angled toward the target from the nearest accessible location did disclose traces of fibre on the periphery of the target.

This record of successful drilling gives considerable weight to the hypothesis of a structural control for the genesis of amosite fibre. It should be remembered, however, that the main prerequisite for any fibre development is to have the necessary chemical components for a specific fibre variety. Without the required chemical constituents, no amount of folding, faulting, or alteration can produce any fibre.

It is interesting to consider this structural origin for the genesis of chrysotile fibre as well, because the effects of faulting, folding, and dilation by shearing or intrusion almost invariably occur in close proximity to fibre occurrences.

FACTORS AFFECTING TONNAGE AND GRADE

Numerous factors affect both the tonnage and grade of chrysotile asbestos deposits which in turn govern the shape, size and exploitation of the orebodies. Most chrysotile orebodies are irregular in shape and are often podiform, tapering in depth or along strike.

Ore and barren zones occur within the ultramafic host rocks. These zones are distinguished and defined by controlling factors operative within the host rock.

The ore zones are created by suitable fracturing, tensional stress conditions and are adjacent to more pronounced hydrothermal activity. Serpentinization is controlled by the fractures, shears and joints in the rock and the quantity of fibre is considerably greater in suitably stressed areas. Several factors affect the grade:

fracturing of the serpentinized host rock creates either: an irregular fracture pattern, forming a stockwork fibre; regular fractures formed sub-parallel to contacts between host and country rocks, forming parallel ribbon fibre; shearing along serpentinized planes, forming slip fibre; or random fracturing with changing stress conditions, forming mass fibre. Degree, persistence and orientation are important

fibre quality varies between soft and silky to harsh and brittle. The former is developed where the host rocks contain higher MgO and lower Fe_2O_3, CaO and Al_2O_3. The latter is formed in rocks containing higher Fe_2O_3 and Al_2O_3. Magnetite, talc, chlorite, brucite, awaruite, ferrit-chromite and magnesite also affects quality. These properties affect drainage and dispersion as well as the behaviour of the opened fibre during grading.

fibre length is affected by partings, kinks and crenulations caused by change in stress condition and direction. Determine whether the length distribution is random or zoned.

kinks, crenulations: kinks represent potential weakness in the fibre. Crenulations often mean a potentially weaker fibre and an increase in fibre-to-fibre cohesion because of the interlocking effect.

sidewall adhesion: High adhesion would mean "frozen" fibre with the fibre adhering to the broken rock. Low adhesion or loose fibre results in a high percentage of free fibre in the fine fraction mined ore but also ready release of fibre in milling, which permits early rejection of waste rock.

fibre cohension: The degree of cohesion is often influenced by some of the above factors, but may also be affected by fine interfibrillar coatings. Low cohesion often indicates good wet dispersion properties.

tensile strength is affected by impurities weakening the interfibrillar bonds and excessive heat on the fibre.

flexibility is affected by imperfections in the crystal structure, excessive serpentine, brucite, magnetite and magnesite.

Several factors affect the orebody host rock which may be critical during exploitation, including:

Orebody joints. Attitude, interval, joint condition (smoothness, straightness, slickensides, gouge) cementing wholly or partially, and the presence of fibre must be determined.

Orebody competency. An overall assessment of the orebody competency must be made, preferably in terms of the rock mass classification, as discussed later.

Footwall zone. The footwall of the orebody must be investigated for a distance embracing the mining layout. If the orebody contact is economic, the underlying fibre zone must be valued and defined. The lithology, structural geology and competency of this zone to be investigated.

Hangingwall zone. A sound knowledge is required. Fibre values affecting dilution and caveability must be determined, and major structures which can affect subsidence angles located.

The barren and uneconomic zones are due to:

shearing, often comprising finely cleaved serpentine, slip picrolite and slip fibre, and minor talc zones.

steatization forming talc carbonate and talc alteration, internal harsh and brittle fibre zones.

partial serpentinization causes the host rock to be too high in Fe_2O_3 and Al_2O_3, thereby not conditioning the rocks favourably and producing harsh fibre.

deformation intensity produces unfavourable fracturing of the host rock whether it is too high or too low.

excessive magnetite shortens fibre length.

unsuitable layered complexes with too little or too few ultramafic units.

faults disrupting the orebodies.

intrusives which create barren zones in their immediate vicinity.

prograde metamorphism which forms antigorite from chrysotile.

changing stress conditions creates random mass fibre or reduces the formation of stress-controlled dilation seams.

depth of weathering, which forms brittle fibre in the weathered zone.

These controlling factors affect the:

shape of the orebody. It is "stratabound" within an ultramafic unit but it is podiform in depth and elliptical in length.

size which is structurally controlled and is dependent on channelway development and the amount and intensity of alteration by hydrothermal fluids.

continuity. The ultramafic is continuous but the orebody is discontinuous within it.

attitude which is generally regular. The plunge is dependent upon structural control and seam orientation, where the stockwork pattern may have a preferred, dominant orientation.

definition of the orebody which is usually an assay cut-off as the orebody is developed within an alteration envelope.

classification of the orebody, which is strongly zoned with the economic fibre generally furtherest away from the influence of alteration adjacent to the channelways. These conduits form barren zones as a result. Zonation is also produced by partial serpentinization.

ground conditions. The talcy nature of the serpentinized ultramafic usually produces poor to moderate mining conditions.

The effects of these controls on the shape, size and exploitation of these orebodies are provided by several examples below.

The serpentinization process is initially dependent on faults, fractures, shears and joint systems which provide conduits and channelways to condition the ultramafic rocks for potential fibre growth in favourable areas. Partial serpentinization produces a dark green rock which has a higher Fe content and is host to a harsh, usually subeconomic, fibre. This fibre often contains abundant disseminated magnetite grains which affects the fibre quality. Moderate to total serpentinization produces a light green rock which has a lower Fe content and is host to a silky, economic fibre. Serpentinization thus produces a zoned effect within the orebody, which usually creates a zoning of values within the ore zone.

Later CO_2- bearing hydrothermal solutions may use these channelways which alter the serpentinized ultramafic rocks to form talc-carbonate and talc zones which steatize the host rocks and alters any economic fibre to brittle uneconomic fibre. Figure 5.1 clearly illustrates this effect which separates the orebody into irregular pods of fibre.

Alteration and serpentinization produce characteristic envelopes around the orebodies giving the impression of isoclinal folding (Figures 5.2 and 5.4).

The effects of faulting are illustrated at Msauli, eastern Transvaal where economic chrysotile fibre mineralization is confined to the apple green serpentinized dunite unit. Four orebodies occur as separate lenticular, steeply dipping zones (60°-70° ESE) within poorly mineralized to barren apple green ultramafic striking NE over a 3 km strike length (Figure 5.3).

The ore zones are closely associated with, and generally bounded by, the SW trending Maanhaar fault zone. The economic fibre bodies are irregularly developed within the apple green ultramafics, the extent of development being controlled by the shear zones. The mineralized zones consist of a massive stockwork of randomly orientated cross fibres

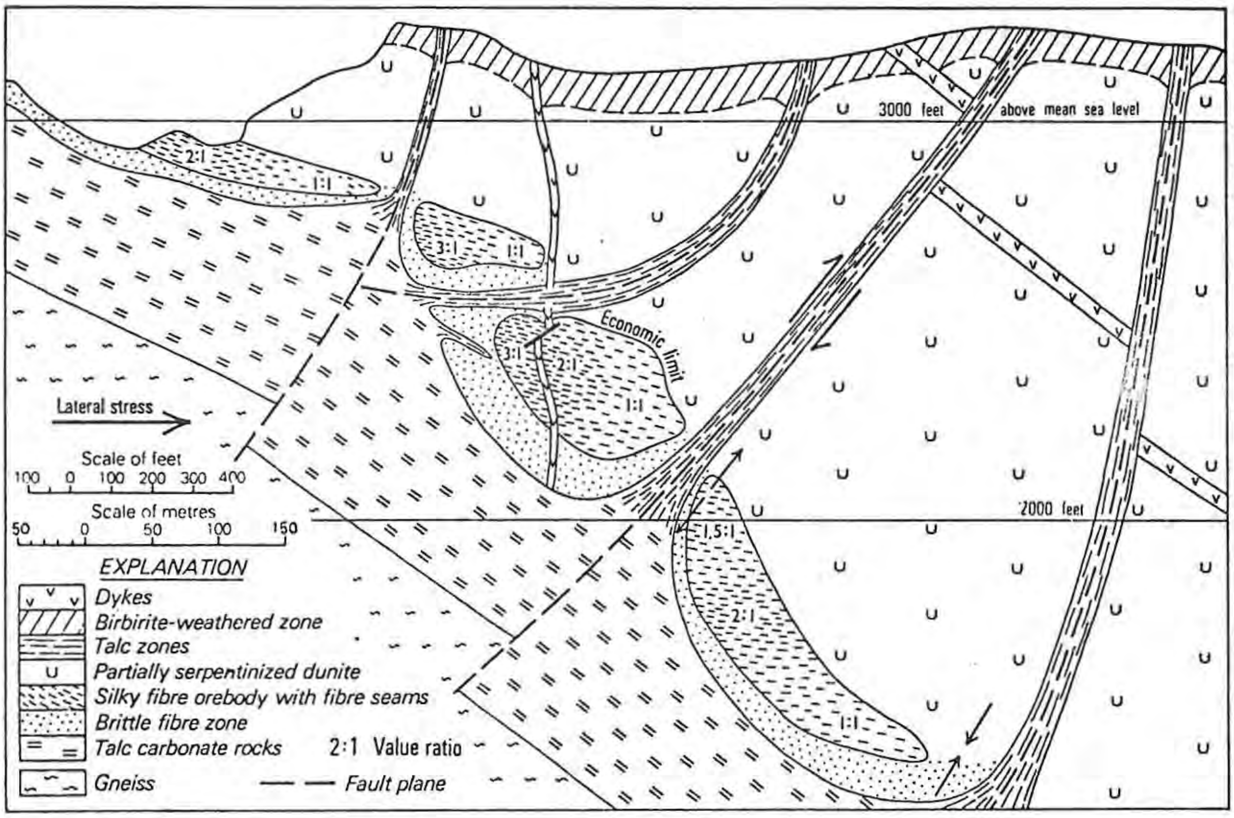


Figure 5.1: A composite section through the Shabanie mine, Zimbabwe, illustrating orebody shape and the effect of faulting on the orebodies. Alteration of the host rock is initiated along faults ultimately affecting size and shape of the ore zones. (Martin, 1978)

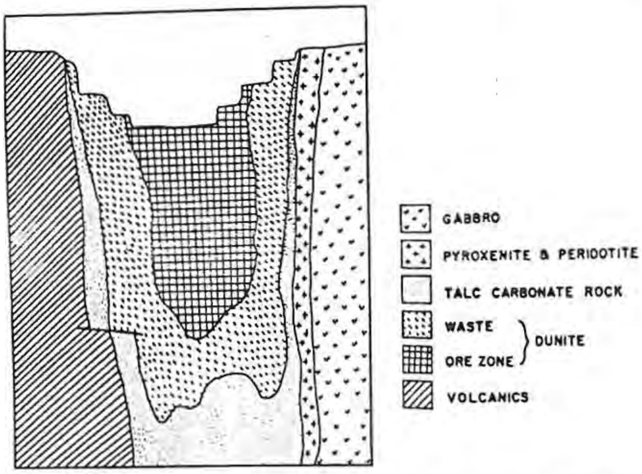


Figure 5.2: Diagrammatic section of the Munro Sill illustrating the alteration envelope developed around the ore zone dunite. (Grubb, 1962)

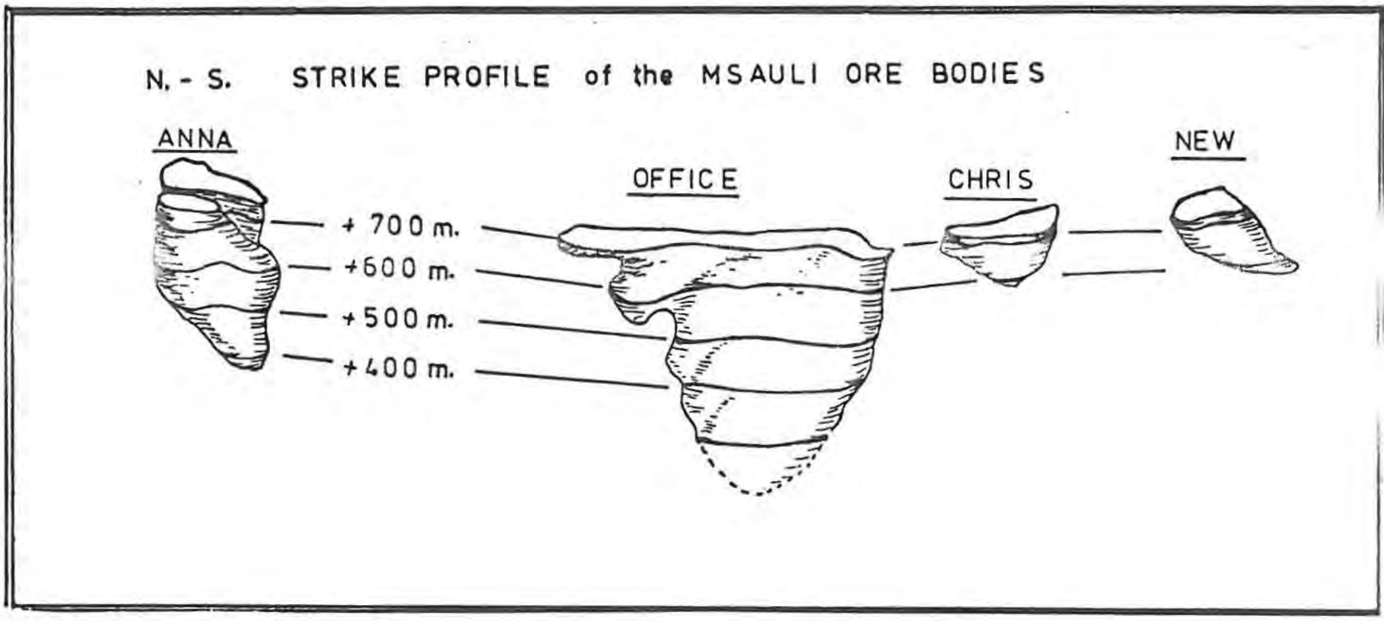


Figure 5.3: North-south longitudinal projection of the four chrysotile asbestos orebodies, defined by a 4% cut off. (Voigt et al., 1980)

developed within tensional fractures. These fractures are orientated obliquely to a network of slickensided joints and fractures containing slip fibre, magnetite and magnesite.

Economic fibre is developed in the host rocks that have higher MgO and lower $Fe_2 O_3$, Ca O and $Al_2 O_3$ contents which, in the Msauli area, always coincides with a characteristic light apple green serpentinized ultramafic. The higher $Fe_2 O_3$ and $Al_2 O_3$ content of the dark green ultramafic appears to hamper good fibre development and is usually harsher and of poorer quality than the ore zone fibre.

The Anna orebody consists of two ore zones, about 70 x 200 m in extent, separated by a wide sheared zone (Figure 5.4). Northwards the ore zone pinches out against the main shear zone and is terminated in the south by an E-W trending dyke. The western limb has a 250 m depth at about 60° ESE while the eastern limb has a steeper dip and abutts against the dividing shear zone at 150 m depth. The eastern zone contains longer fibre while shorter fibre is more prevalent in the western limb with scattered longer fibre lenses. The irregular shapes

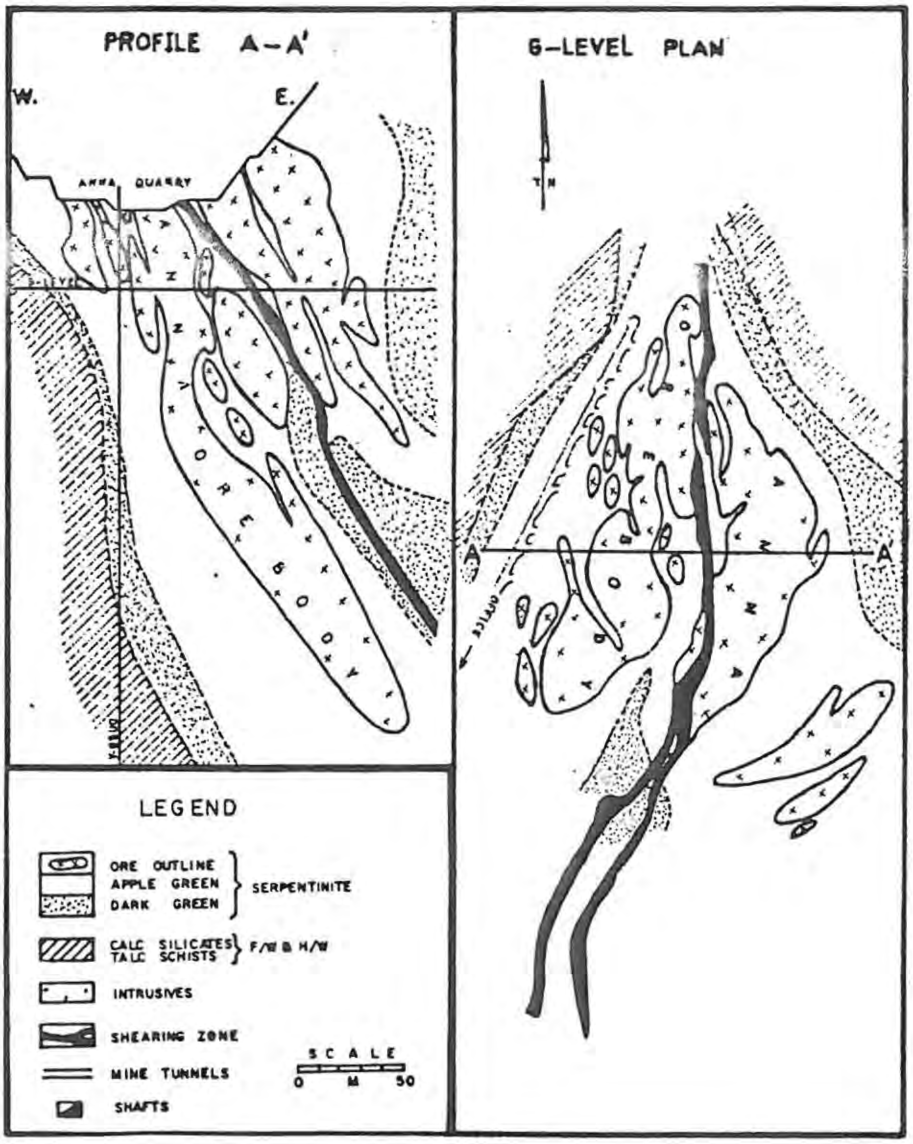


Figure 5.4: The Anna orebody illustrating the irregular shapes of the ore zone developed within apple green serpentinized dunite, and the effect of the prominent Maanhaar shear zone. (Voigt et al., 1980)

of the ore zones developed within the orebody makes evaluation and exploitation difficult. Changing stress conditions during fibre growth, internal fractures, joints and shears have all contributed to these irregular shapes and sizes of the ore zones.

The Shabanie mine in Zimbabwe is the largest occurrence of chrysotile fibre in southern Africa and is described by Laubscher (in Martin, 1978). The main fibre development is confined to the central footwall portion of the dunite. Hydrothermal activity was more pronounced, and faulting has created the right stress environment.

The carbon dioxide content of the hydrothermal solutions gradually increased, and the silky fibre and serpentine were altered to brittle fibre in a carbonated serpentine and, finally, to talc pseudomorphs in talc carbonate rocks. The fault zones and contiguous rocks were also altered to form the prominent talc zones.

The orebodies are, therefore, separated along strike and down dip by dykes and talc zones, producing a highly irregular podiform pattern, clearly illustrated in Figure 5.5. There is also a variation in value and length distribution within the orebodies and from orebody to orebody, and boreholes to depths of 600 metres have indicated similar values and lengths.

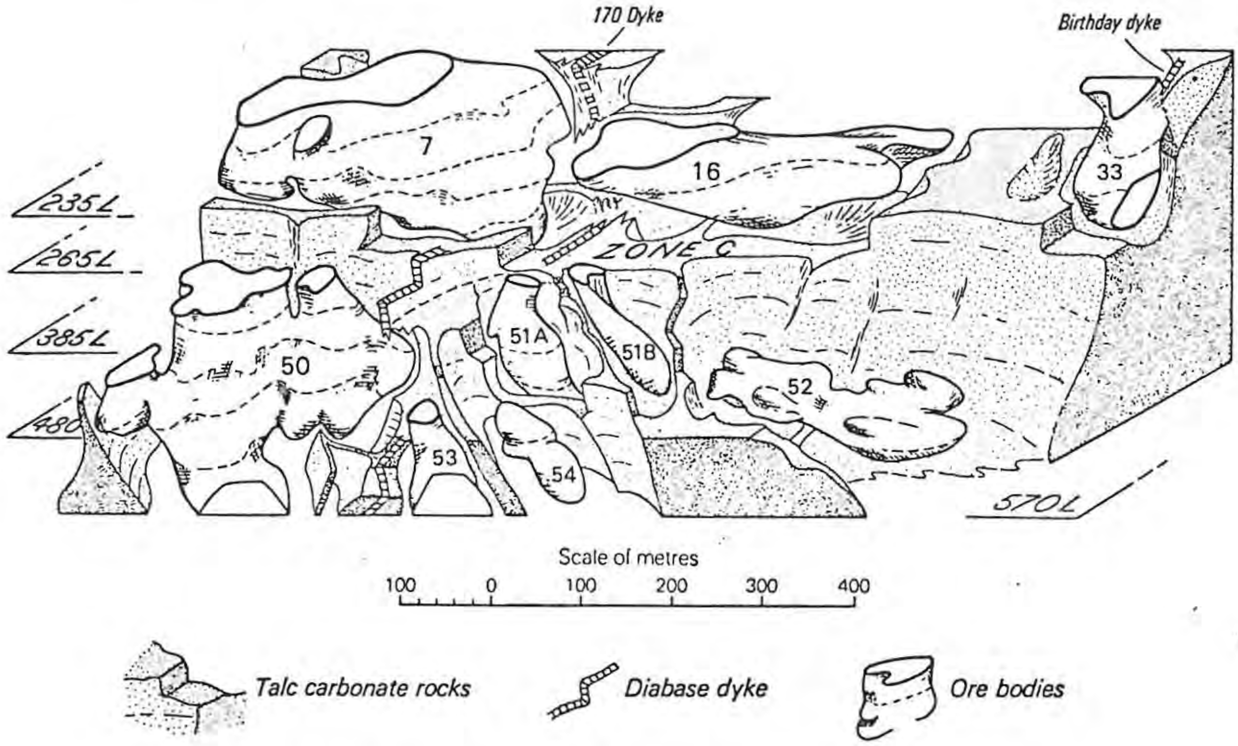


Figure 5.5: Isometric diagram of the irregular shapes and sizes of the orebodies at Shabanie mine, Zimbabwe. The difficult evaluation of ore and complex nature of the mining environment can be appreciated. (Martin, 1978)

EVALUATION OF ASBESTOS DEPOSITS

The evaluation of chrysotile asbestos deposits have been fairly comprehensively described by Oughtred (1952), Shurtz (1966), Bichan (1966), Dean and Mann (1968), Conn and Mann (1971), Winson (1975), Cossette and Delvaux (1979), Laubscher (1980a) and Mann (1981). Evaluation methods at Msauli mine have been provided by E. Sutton (pers. comm., 1982).

No published literature can be located on the evaluation methods of crocidolite or amosite asbestos. A personal visit to the former area has, however, provided some information (Gefco geological staff, pers. comm., 1982).

The evaluation of any asbestos deposit entails the determination of its size, shape, grade and quality of its fibre. Dimensions of a suitable target area are identified and delineated by conventional exploration methods such as mapping, geophysical and geochemical surveys, trenching, pitting and diamond drilling.

This evaluation depends not only upon the total quantity of asbestos present but also upon the quality, based on the numerous physical properties of the fibres, such as fibre length, tensile strength, flexibility, harshness, colour, dust content and degree of fiberization. The determination of grade cannot be based on a simple chemical analysis as both the fibre and wallrock have essentially the same chemical composition.

The commercial value of orebodies vary from one another, and may also fluctuate significantly within a given ore deposit, as illustrated in Figure 5.1. As the price of fibre varies considerably depending on its length, the use of grade based solely on its percentage fibre content is of little significance. Instead, the product of these two variables, expressed in local currency per ton of rock, offers a far more meaningful value which can be used for direct comparison in the final evaluation.

Techniques used in the evaluation of asbestos deposits are visual sampling, bulk sampling, milling of the fibre samples, evaluation of the fibre samples and ore reserve estimation.

Visual Sampling

Sampling of rock exposures or diamond drill core is an accepted technique with certain limitations. Greatest accuracy is achieved where the fibre seams are parallel and do not show marked length variation over short distances. Sampling must include the angle of the seam with the sampling line and the angle of the fibre with the seam wall. In sampling underground exposures, problems are often experienced in highly jointed rock masses, as the ground will break to a joint. The accepted length interval of visual sampling is 1,5 mm, and if fibre is measured in multiples of this unit the length distribution can be obtained. However, a grade distribution cannot be obtained by this technique and attempts to do so lead to over-estimation of longer grades. In borehole core sampling, the core must be split, as the fluffing of the fibre on the outside of the core leads to enhanced valuation as fibre fractures are concealed. Sampling should be done along a line drawn down the centre of the split core and the sampler's personal bias-correcting factor must be established in relation to milling tests (Laubscher, 1980a).

Visual sampling is useful in the evaluation of asbestos, particularly : in surface exposures where fibre is the only indication of a potential orebody; in narrow reef deposits where reef development offers a better sampling exposure than a borehole intersection because the ratio of lateral extent to width is very high; where good core recovery is difficult because adhesion and cohesion are poor and the host rock is friable; in underground development as an aid to zoning of values; in borehole core, to decide on core mill sample lengths for core milling and to break down these results to shorter lengths if so desired, as for cube evaluation.

Drill core evaluation methods are comprehensively described in Bichan (1966), Dean and Mann (1968), Conn and Mann (1971), Winson (1975), and Mann (1981). Each vein of cross-fibre is logged and the length carefully measured and recorded in multiples of 1/16 inch (or millimetres). Allowance must be made for inclined veins at an angle to the core length and a correction factor is applied to obtain true fibre lengths. This visual reading usually gives an indicated lower yield of a higher value fibre than a corresponding milling test. This is because visual readings disregard fibre lengths of less than 1/16 inch which are recovered in milling. Most of the discrepancies are compensating, however, and once a suitable correction factor is used, the ore values disclosed by the two methods are generally comparable. This method is laborious, especially when a stockwork fibre pattern is intersected having random vein orientations.

Slip fibre cannot be determined by this method and only test milling of a bulk sample can evaluate this type.

At Msauli the technique is to determine the ore zone by visual logging, without measuring fibre widths or orientations, and separate the whole, unsplit core into suitable sample lengths. Samples are milled in a test plant to obtain fibre percentage and a Rand per ton (R/t) value for each sample (E. Sutton, pers. comm., 1982). The lengthy procedure of splitting and measuring fibre veins is avoided but it is not known whether this technique would yield comparable results to that technique proposed by Laubscher (1980a).

There are two R/t parameters applied at Msauli : the R/t (ore) is a guide to the amount of long fibre (+ 14 mesh) in the ore, while the R/t (fibre) indicates the total percentage fibre including - 200 mesh dust. The former is a guide to mining, the latter a guide to milling. The rule of thumb relationship is:

$$\frac{\text{R/t (ore)} \times 100}{\text{\% fibre}} = \text{R/t (fibre)}$$

Regardless of the method used in evaluating asbestos ore, the final result should give the fibre value, the yield and the ore value in local currency per ton.

Face readings either on surface outcrops or in underground workings can take the form of channel sampling or linear readings along either wall of a drift or crosscut. In situ fracturing makes it difficult to obtain representative results using the latter method.

Bulk Sampling

The various methods of logging and sampling seldom give entirely dependable results. The conditions found at an operating mine cannot easily be simulated in the test plant or laboratory. The fibre is subjected to a good deal of handling, some rather severe, from the time of blasting to the final product. The fibres, as a consequence, suffer some breakage in the process.

Bulk sampling is often resorted to as a means to check and arrive at a suitable factor to be applied to drill core data. Core drilling of 30 cm diameter holes provides a large sample which is extremely useful where depth of weathering or overburden is excessive. Large tonnage samples are usually obtained from trial mining pits or underground workings. Winson (1975) and Mann (1981) describe bulk sampling to obtain a "yield correction factor" to compare in situ ore values with milling values.

Milling and Evaluating Fibre Samples

Milling of diamond drill core, cuttings from churn and percussion drilling and bulk samples are done with either a pilot or test plant or a large-scale mill. It is imperative that fibre samples are milled so that the recovered fibre can be evaluated relative to current grades and mill performance.

A sample plant must be designed to recover all fibres above a specified length, so that it can be regarded as 100 per cent efficient and mill performance related to it. If not, then the assay result must always be suspect. Few sample plants meet these requirements and the fibre is often degraded. Experiments on the mechanical and wet dispersion opening of fibre have shown that there is a loss of length determined by fibre length measurements. It is, therefore, essential that fibre recovered in the sample plant has the same degree of opening as in production.

Evaluation of fibre samples is just as important as any other part of orebody valuation. However, laboratory tests are often rather haphazard. The limitations of laboratory tools must be recognised. The object of the valuation is to relate the absolute fibre content of the deposit to the mill recovery, grade distribution and fibre quality.

Cossette and Delvaux (1979) describe in detail all the methods used for the evaluation of fibre grade including the Quebec Standard Test which is a basic method of fibre evaluation. Length classification tests are done using the Canadian Box (dry) test, the Bauer-McNett or Turner and Newall (wet) classifiers. Fiberization tests can be done using the Rapid Surface area, whereas the Turner and Newall Elutriation test determines the proportion of fiberized fibre in any grade of asbestos.

Tensile strength can be evaluated on the Fibre Strength Unit. Most asbestos cement fibre grades marketed at present are valued for the reinforcing strength they impart to various products. It is imperative, therefore, that any evaluation of a chrysotile deposit include Strength Unit tests, a laboratory test involving the testing of an asbestos cement tile made with the subject fibre. Once the inherent strength of the fibre from a particular orebody has been determined it is usually possible to equate strength to length distribution and dust content measurements.

According to Laubscher (1980a) certain established laboratory tools are extremely inaccurate, namely the Canadian Box Test, the Rapid Surface area and the Bauer-McNett. In his experience, fibre evaluation is best done by the T and N Classifier, Suter Comb and fibre pad dispersion techniques. For example, the length distribution on classifier screens is illustrated in Table 6.1.

mm.	0	1,6	3,2	4,8	6,4	7,9	9.5	11,1	12,7	14,3	15,9	17,5	19,1	20,6	22,2	23,8	25,4	27,0	28,6	30,2	31,8
inch	0	1/16	2/16	3/16	4/16	5/16	6/16	7/16	8/16	9/16	10/16	11/16	12/16	13/16	14/16	15/16	16/16	17/16	18/16	19/16	20/16
+7	0	0	1,3	5,2	9,5	13,3	14,5	13,6	8,5	8,6	9,2	4,7	3,1	2,3	1,8	1,6	1,1	0,4	0,4	0,2	0,7
+14	0	0,7	7,6	30,9	29,3	16,8	9,3	3,5	1,7	0,1	0,1	0	0	0	0	0	0	0	0	0	0
+25	0,8	18,3	49,6	25,2	5,1	0,9	0,1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
+50	15,5	77,9	6,6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
+200	93,4	6,6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 6.1: Distribution of fibre lengths in + 7, + 14, + 25, + 50 and + 200 T and N Classifier fractions. Combined results of all grades from a long fibre deposit. (Laubscher, 1980a)

Mill recovery factors are determined from head and discard samples milled in the same sample plant. The head sample gives the most accurate determination of the mill recovery factors. However, great care must be taken in sampling the mill feed because of the "nugget effect" of the longer fibre seams. Concurrent with the head sampling is the taking of accurate discard samples. In fact, all mills should have an accurate discard sampling procedure but, regrettably, asbestos milling often does not follow this accepted metallurgical practice and discard sampling is haphazard and inaccurate. Sporadic head sampling and routine discard sampling will ensure accurate mill recovery factors. Discard sampling alone cannot be used as it ignores fibre degradation in the milling operation.

At Msauli, production efficiency factors at present are as follows (B. Reed, pers. comm., 1982):-

a) in situ ore to mill feed :
   long fibre = 83,68%; 16,32% dilution
   total fibre = 88,33%; 11,67% dilution

b) mill feed to saleable product:
   long fibre = 67,02%; 32,98% discard
   total fibre = 80,55%; 19,45% discard

The long fibre and total fibre figures in b) are a measure of mill efficiency.

Ore Reserves and Potential Resources

There are four estimation methods which can be applied for ore reserve calculations, described by Laubscher (1980a), Winson (1975) and Mann (1981), namely the polygonal, cross section, contoured cross section and cube (mine block) evaluation methods. Shurtz (1966) describes statistical controls in the evaluation of the deposit near Copperopolis, California, but found that evaluation was difficult because results of the milling tests were directly dependent upon the methods used.

Once the assay value of the sample is correct, the sampling coverage must be adequate to calculate tonnage and value. To define the orebody and to arrive at the value, the geology must be clearly understood, involving value distribution trends or anisotropy, which must be clear to all involved in mining the deposit, for it affects draw control tonnages as well as ore reserve calculation.

Orebody limits are invariably based on an economic cutoff. With strong local anisotropy, the outline will be irregular - often caused by blobs of ore separated from the main concentration by low-value zones. To be included in the ore outline, the ore blob and the unpay zone combined vertically must then exceed the cutoff value, as this is the direction that ore will flow. If the hangingwall limit is in doubt, a conservative approach should be adopted because in caving these high-value zones act as dilution in the overall production tonnes.

The polygonal weighting factor method for block grade estimates from borehole results overlooks the anisotropies of chrysotile asbestos orebodies and leads to over-valueing. If the value trends or drift can be established, then the weighting directions and magnitude can be calculated. As the orebodies are invariably three-dimensional, value trend vectors may not coincide with the horizontal plane (plans) or any established vertical section.

In serpentinite chrysotile bodies, cymoid structures are common, giving rise to pods of stockwork ore, often surrounded by shear zones of low value. In the partially serpentinised dunites and peridotites of southern Africa, fibre seams are sub-parallel with minimum variation along strike and maximum across dip.

The cross section method, or groups of cross sections, is used by weighting the individual holes in each section and thereby determining the average grade for each section.

Contoured cross sections uses contouring which is based on a reasonable interpolation of the intervening area between drill holes. This method permits the estimator to make use of all available geological information in the interpolation. In open pit operations, contoured horizontal sections may be prepared in this manner to correspond with expected mining level intervals, and these serve as useful guides to mining. Separate horizontal sections contoured for rock value and fibre value per ton permit the mine operator to produce a more balanced mill feed in respect to both fibre content and grades.

Cube valuation consists of dividing the block into cubes which will fit into the mining layout, for example, drawpoint spacing. The centre of each cube is coordinated and its value computed from the surrounding sample intersections. Where there is no zoning of values, weighting values decreasing isotropically would be used. Weighting factors should recognise any zoning of values or trend, thus a plot of all points with equal weighting factors would have an ellipsoidal shape; for example, at a distance of 20 m, the long axis would have a weighting factor of 100, the intermediate a factor of 50 and the short axis a factor of 25. The values are arbitrary as long as the relationship is correct. Boundary conditions are imposed on the size of the weighting shape, i.e. the ellipse will only use sample values which fall within its dimensions of, say, 40, 20, 10 metres. The size of the weighting body (shape) will be dictated by the range beyond which samples do not influence each other; this is obtained from the variogram.

Values across contacts will not be used to value the ore in that compartment. Sample values nearest the point being valued will eliminate any sample values further away on the same line (30° arc).

The low-value zones often exhibit nugget effects because of local abnormally high values, and these intersections should not have the same weighting as the predominantly low values as would be the case with the polygonal method.

It is likely that sophisticated geostatistical methods such as kriging will not produce more accurate estimations than those obtained using the cube method because of the bulk mining methods employed for extraction and the grade of the ore zone which is usually somewhat higher than the cut-off grade. Selective mining methods are not used for asbestos exploitation hence absolutely accurate grade estimation may not be necessary. Arithmetic mean averages are calculated at Msauli and used to obtain weighted average values (in situ grade) for both triangular and/or diamond-shaped mining blocks. This is found to be an adequate method (E. Sutton, pers. comm., 1982). The variable fibre distribution within the ore zone is compensated by dilution factors especially fibre length, which can sometimes be reduced due to severe handling between blasting and eventual milling operations. Reconciliation of results from the mill head grade, muck pile sampling and in situ grade estimations should determine whether the ore reserve estimation method is accurate enough for a particular mining operation.

The presentation of ore reserves and potential resources is often haphazard. Ore reserve is that tonnage of valued payable ore within the orebody limits, as defined by the Geology Department, and which can be mined at a profit and handled through the existing shaft system, or quarried, i.e. irrespective of mining method. Available ore reserve is that portion of the in-situ reserve which can be extracted by the foreseeable mining methods. Ore tonnes for draw are those tonnes of available ore that will be drawn, net of extraction losses. Production tonnes are the draw ore plus dilution, at value calculated from the respective values of the draw ore and the dilution; this represents the most accurate assessment of the tonnes that will be sent to the mill, and its average value must cover all costs of mining and planned profit. The production tonnes are used for fibre production forecasts and short-term planning.

Potential resources is that tonnage of currently unextractable fibre-bearing ground which has a higher-than-pay-limit value, and on which long term planning is based. As the state of valuation of potential resources can vary, the following sub-divisions and definitions are recommended. Tonnage and value should allow for assumed extraction losses and dilution effects:

Probable ore is that ore not catered for by the shaft system, but whose value and tonnage can be accepted with confidence.

Prospective ore is that tonnage of payable fibre-bearing ground with a conservative tonnage and defined only by exploratory drilling.

Inferred ore is that tonnage of fibre-bearing ground for which quantitative estimates are based on broad knowledge of the geologic character of the deposit, and on few, if any, sample intersections. It is assumed that values would be above pay limit and located in explorable areas.

In general, ore reserve and potential resource schedules should be a comprehensive record of all payable, or potentially payable, fibre-bearing ground.

Crocidolite Fibre Evaluation

Potential ore-bearing zones are evaluated by stratigraphic drilling through the shallowly dipping iron formation units. Individual ore bodies are eventually evaluated on a 70 m square grid to define the limits of the orebody. The crocidolite asbestos mineralization in the borehole core is visually evaluated by measuring the length of the fibre and the proportion of fibre. Crocidolite fibre greater than 3 mm in length is measured in 10 cm sections. Fibre less than 3 mm is not measured as this size fraction is not recovered in the plant.

The total length of fibre in each 10 cm sample gives the total volume percentage of fibre within the sample, expressed as a percentage of the total thickness of the intersected reef. The distribution of individual fibre lengths gives an indication of the variation in the fibre grade. The measuring of the length of fibre in the core is a simple but often inaccurate method of obtaining the grade of potential ore zones. This is because kink zones and discontinuities within the fibre bands are not always taken into account. A more accurate method would be to process the borehole core in a pilot plant which would be directly correlatable with the final product. A more accurate size distribution of the ore would be obtained which would give an indication of the value and marketability of the crocidolite asbestos mineralization.

The orebody is subjectively contoured to a minimum cut-off of 6% over a minimum width of 1,2 m. All intersections within this boundary are then used to define triangles, and the in situ tonnages are calculated assuming a linear variation in thickness between holes using an S.G. of 3,375. The grade for the areas within each triangle are obtained by weighting grade x thickness for each apex. Due to the variation in the quality of the fibres a Rands per ton figure is also calculated according to fibre length. This in situ tonnage does not relate to the milled tonnage because the host iron formation contains significant amounts of magnetite which increases the S.G. of the ore.

During the mining operations the stope faces are sampled at 6 m intervals using the same visual estimation technique as before. The grade is more variable in folded areas and so these are sampled every 3 m. However the estimated grade, which is a volume percent, does not correspond to the actual grade processed by the plant, which is a weight percent, because this constant S.G.factor is used for tonnage estimates even though the S.G. of the ore is variable.

To summarize, for the proper evaluation of an asbestos orebody the factors to be considered are:

1) the percentage fibre in the host rock.

2) the percentage extraction of the fibre : does the fibre separate easily from the host rock (sidewall adhesion)?; is the fibre "free milling" or "tight fibre" (fibre cohesion)?; how does the host rock respond to crushing (granular or compact)?

3) the proportional amounts of different lengths of fibre: how will milling affect these lengths? The greater the percentage of long fibre extracted, the higher the value.

4) the physical properties of the fibre such as tensile strength, filtration rate, magnetic and colour ratings, and dust content.

The critical factors in evaluating economic asbestos deposits are, therefore, the fibre quality (flexibility, fiberization and tensile strength), fibre length and percentage fibre, as the marketability of the product is highly dependent on the grade of the fibre.

The actual grading of the asbestos after milling is discussed in Chapter 8, and this grading will determine the value of the product.

PLANNING AND MINE DEVELOPMENT

Extensive use has been made of Laubscher (1980 b) who describes in detail both the planning and underground mining of chrysotile asbestos deposits. Numerous other writers have described mining practices and geotechnical parameters associated with asbestos mining, including: Foster and Harris (1957), Hall and McMenamin (1966), Evans (1975), Laubscher (1975), Heslop (1976), Laubscher and Taylor (1976), McMurray (1976), Ferguson (1977), Laubscher (1977), Brown and Ferguson (1979), Taylor (1980), Wen (1980) and Williams (1981).

The mining geologist should have an important role in all mining operations, but too often this is limited to initial exploration and valuation. It is expected, but not accepted by most South African mining companies, that the geologists be involved from the initial stages to the exhaustion of the orebodies. This presumes that the geologist has both the knowledge and the ability to communicate with others involved in mining. Lack of communication and incorrect presentation of data have often led to major mining problems.

The geological environment must be clearly understood by all concerned with mine planning; this encompasses shape of orebody, surrounding rock types, value distribution in ore body and periphery, structural geology, strength of footwall, orebody and hangingwall rocks.

To present the data in a practical form, it is recommended that the geomechanics rock mass classification be used. Such a technique must be straightforward, so that it may form part of normal mining geology. Highly sophisticated techniques are time-consuming, of doubtful benefit and beyond the resources of most mines. The approach adopted here is to assign the rock mass in *in-situ* value, regardless of its spatial position, provided that the stress environment does not exceed 40 MPa (Laubscher, 1977).

Asbestos ore can be degraded by the adoption of unsuitable mining methods or procedures, and otherwise normal practices sometimes have to be avoided, or specially regulated in asbestos mining. Block caving is known to cause some attrition of the fibre and the use of scrapers is considered to be detrimental to the ore.

Contamination of the fibres by wood or any combustible materials can be very serious and timber supports and even wooden socket plugs are avoided. Iron wires are preferred to copper wires if electric blasting is practiced as they can be removed, together with any other tramp iron, by magnets.

Even cigarette stubs can be extremely deleterious to the asbestos, and special provision is made underground for their disposal as well as for matches and even paper for sandwich wrapping.

The development of asbestos mining in Canada has been accompanied by a succession of mining practices and equipment. Open pit mining presently prevails but underground methods have included glory holes, shrinkage and sublevel stoping, and block caving.

In southern Africa a large proportion of all the chrysotile is mined by underground methods. The orebodies are generally tabular in shape with a pronounced dip, with the result that the economic limit for quarry mining is reached at a comparatively early stage. Ore widths in the larger mines range from 25 to 60 metres and up to 125 metres. Some orebodies, notably in the Shabani district of Zimbabwe, are quite extensive in length with development extending for 5 km along strike.

Much of the amosite and crocidolite in South Africa has been mined from small, narrow open cuts or adits following the fibre-bearing band. In local areas operations have been developed for larger scale and deeper mining, while the shallow dips enable room and pillar methods to be used.

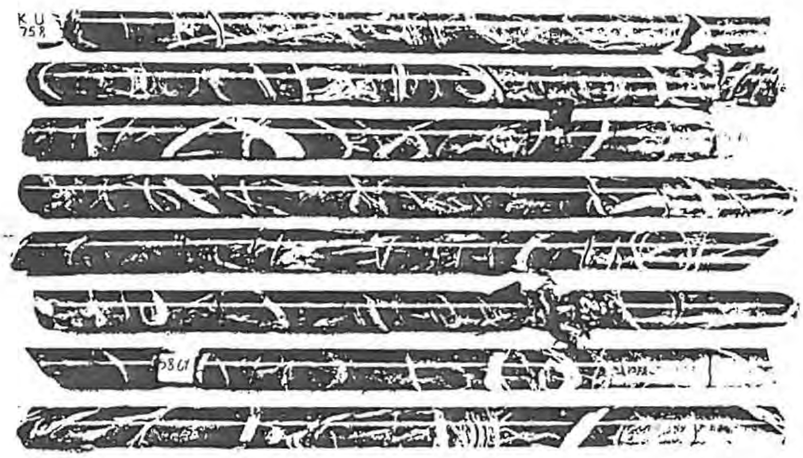
Undoubtedly opencast mining is preferable to underground mining, particularly in chrysotile deposits. However, the change from opencast to underground is often based on an optimistic assessment of underground costs, scant attention being paid to dilution, ore loss, sequence problems, support costs, opening of released fibre, poor fragmentation and low productivity, as well as reduced opportunities for selective mining and the inability to recover hangingwall fibre. Taking these points into consideration, higher overburden ore ratios can be tolerated.

Geotechnical Parameters

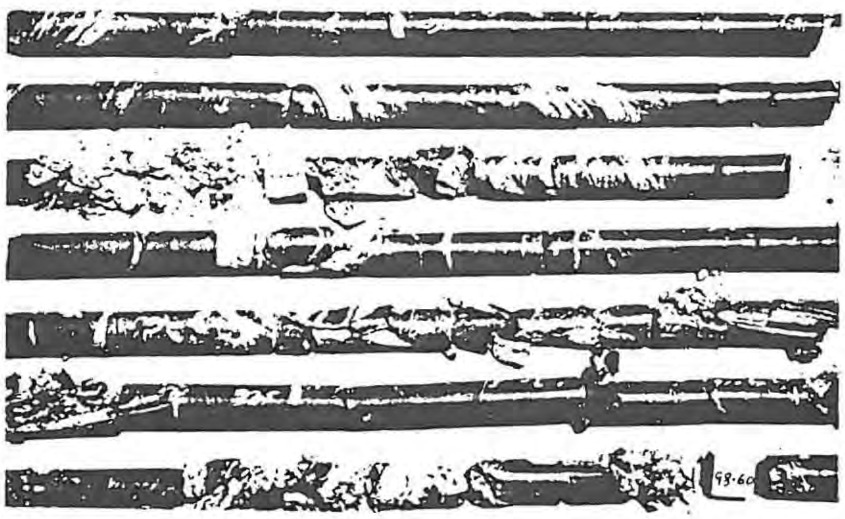
The need for a rock mass classification was initially recognised by Bieniawski (1973) who provided the basis for the geomechanical classification of jointed rock masses, modified by Laubscher (1975, 1977), and Laubscher and Taylor (1976) for mining applications.

The classification requires that the rock mass should be assigned an in situ value regardless of its position in space. In deciding on how the rock mass will behave and the support required, the class is adjusted depending on weathering, field and induced stresses, changes in stress due to mining, the orientation and type of excavation with respect to geological structures and the effect of blasting. The development of this classification is such that it is now possible to classifty the rock mass either by an assessment of rock surfaces in excavations and surface exposures, or entirely by borehole cores (Figure 7.1; Taylor, 1980).

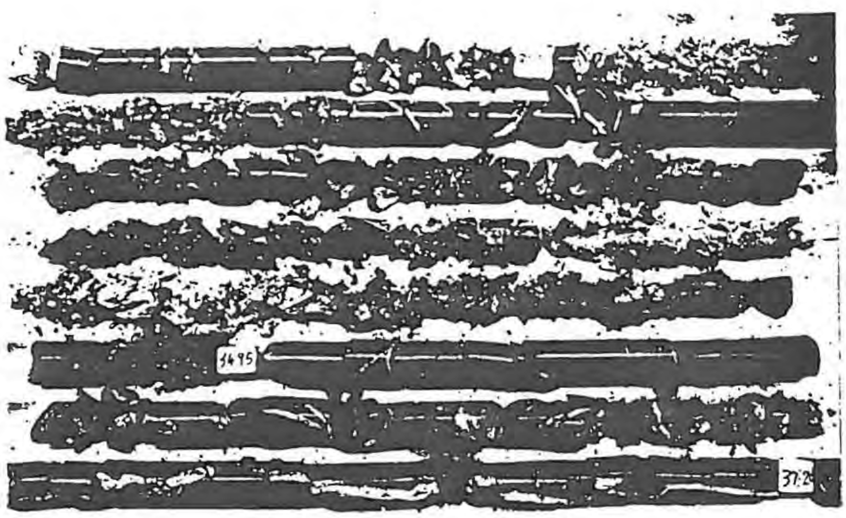
As for all classification investigations (whether in civil or mining engineering) the accuracy of the geomechanics classification depends on the sampling of the area being investigated. The classification is a routine mine geology function, in which the exposures of boreholes depend on the state of preparation of the block for mining. Classification data must be provided at any early stage to ensure correct decisions on mining methods, layout and support requirements. During exploration, development is limited and boreholes are the main source of information (Figure 7.2). Boreholes drilled for valuation purposes may not provide sampling of structure. Detailed geological knowledge of the general area, both on surface and underground, defines the structural units that must be allowed for. Stereographic projections of structures



A. King orebody - rating: 54.



B. Shabanie orebody - rating: 55.



C. King shear zone: rating 25.

Figure 7.1: Examples of diamond drill cores with their rock mass classification ratings. (Taylor, 1980)

from surrounding areas are essential, as the area being investigated can be structurally interpreted from the borehole core data and by extrapolation.

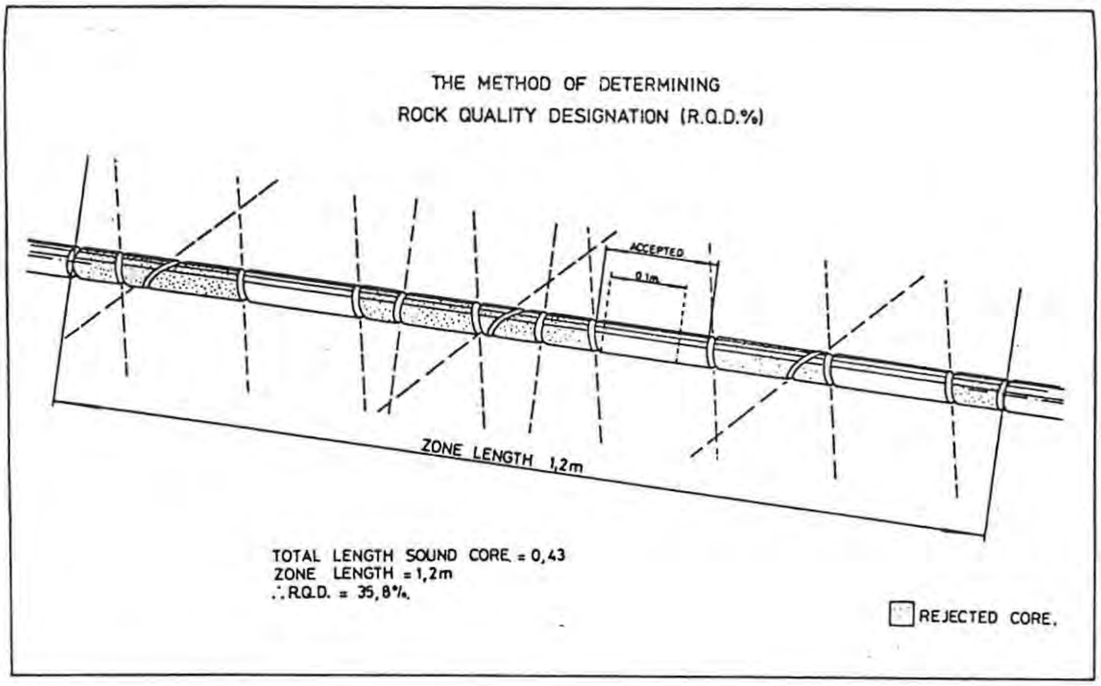


Figure 7.2: The method of determining R.Q.D. from drill core.(see Table 7.1, B). Joints and fractures influence the lengths of whole pieces of core (Taylor, 1980).

A value rating range of 0 - 100 is used to cover all variations in jointed rock masses from very poor to very good. The classification is divided into five classes, with value ratings of 20 per class. Each class is sub-divided into an A and a B sub-class with a ten-point rating. (Table 7.1).

In classification, emphasis is placed on joint condition, which is of great importance in assessing chrysotile asbestos orebodies. Joint condition depends on the angle of friction on that joint, i.e. the tendency of one block to move relative to the other. Also important in assessing serpentinites are shear zones with low ratings which cause the major support and mining problems in chrysotile asbestos bodies, because of their non-recoverable plastic deformation (Figure 7.1, C).

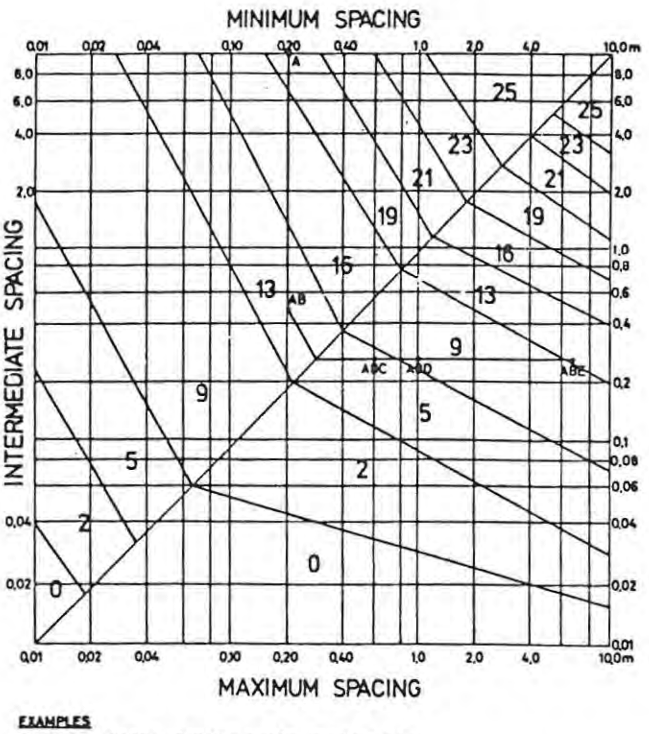
A. MEANING OF THE RATINGS

CLASS	1 A	1 B	2 A	2 B	3 A	3 B	4 A	4 B	5 A	5 B
RATING [Σ1-4 OF B]	100	81	80	61	60	41	40	21	20	0
DESCRIPTION	VERY GOOD		GOOD		FAIR		POOR		VERY POOR	

B BASIS OF THE CLASSIFICATION

1	RQD %	100 – 97		96 – 84	83 – 71	70 – 56	55 – 44	43 – 31	30 – 17	16 – 4	3 – 0	
	RATING (= RQD% x 15/100)	15		14	12	10	8	6	4	2	0	
2	IRS (MPa)	>185	184-165	164-145	144-125	124-105	104-85	84-65	64-45	44-25	24-5	4-0
	RATING (= 0,1xMPa)	20	18	16	14	12	10	8	6	4	2	0
3	JOINT SPACING	REFER C. (BELOW)										
	RATING	25 ——— 0										
4	JOINT CONDITION INCL. GROUND WATER	REFER D. (BELOW)										
	RATING (40 x A x B x C x D/10⁸)	40 ——— 0										

C. RATINGS FOR MULTI JOINT SYSTEMS



EXAMPLES
SPACINGS A = 0,2m, B = 0,45m, C = 0,5m, D = 1,0m, E = 7m
RATINGS A = 19, AB = 13, ABC = 5, ABD = 9, ABE = 13

D. ASSESSMENT OF JOINT CONDITIONS

ACCUMULATIVE % ADJUSTMENT OF POSSIBLE RATING OF 40

PARAMETER	DESCRIPTION		DRY COND	WET CONDITIONS MOIST	MOD PRES 25-125 l/m	SEV PRES > 125 l/m
A JOINT EXPRESSION (large scale irregularities)	WAVY	MULTI-DIRECTIONAL	100	100	95	90
		UNI-DIRECTIONAL	95 90	95 90	90 85	80 75
	CURVED		89 80	85 75	80 70	70 60
	STRAIGHT		79 70	74 65	60	40
B JOINT EXPRESSION. (small scale irregularities or roughness)	VERY ROUGH		100	100	95	90
	STRIATED OR ROUGH		99 85	99 85	80	70
	SMOOTH		84 60	80 55	60	50
	POLISHED		59 50	50 40	30	20
C † JOINT WALL ALTERATION ZONE	STRONGER THAN WALL ROCK		100	100	100	100
	NO ALTERATION		100	100	100	100
	WEAKER THAN WALL ROCK		90	90	90	90
D JOINT FILLING	NO FILL - SURFACE STAINING ONLY		100	100	100	100
	NON SOFTENING & SHEARED MATERIAL (CLAY OR TALC FREE)	COARSE SHEARED	95	90	70	50
		MED SHEARED	90	85	65	45
		FINE SHEARED	85	80	60	40
	SOFT SHEARED MATERIAL (eg TALC)	COARSE SHEARED	70	65	40	20
		MED SHEARED	65	60	35	15
		FINE SHEARED	60	55	30	10
	GOUGE THICKNESS < AMPLITUDE OF IRREG		40	30	10	
	GOUGE THICKNESS > AMPLITUDE OF IRREG		20	10	FLOWING MATERIAL 5	

† IGNORE THIS FACTOR FOR STRAIGHT, POLISHED OR STRAIGHT SMOOTH JOINTS

Table 7.1: The geomechanics classification of jointed rock masses. (Laubscher, 1980 a)

In situ geomechanics classification ratings are plotted on plans as well as described in orebody specifications. Adjustments needed must also be recorded and the adjusted ratings used for planning purposes. Figures 7.3 and 7.4 show the geology and classification data on a cross-section through King Mine.

Rock mechanics investigations are directed towards interpreting the current response of the rock mass and prediction of future response. A monitoring programme tailored to the scale of operation and labour available must be designed with the simplest, cheapest and most comprehensive instrumentation possible. Whilst human nature does not spend money until compelled, experience has shown that monitoring of ground behaviour at an early stage ensures rapid, accurate interpretation when trouble occurs.

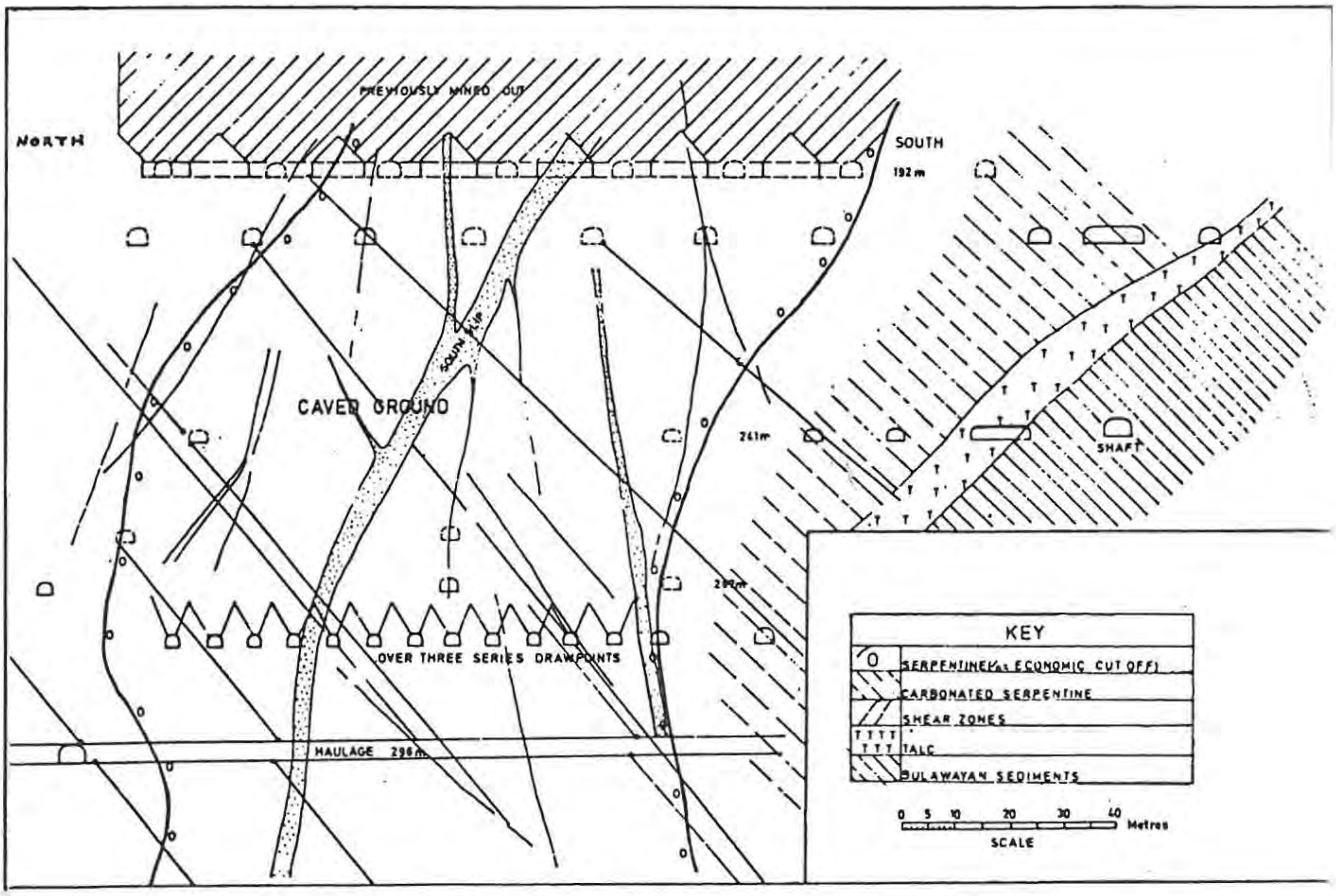


Figure 7.3: Cross section through 2/3 - 3/3 blocks King Mine showing geology and mining layout.
(Laubscher, 1980 a)

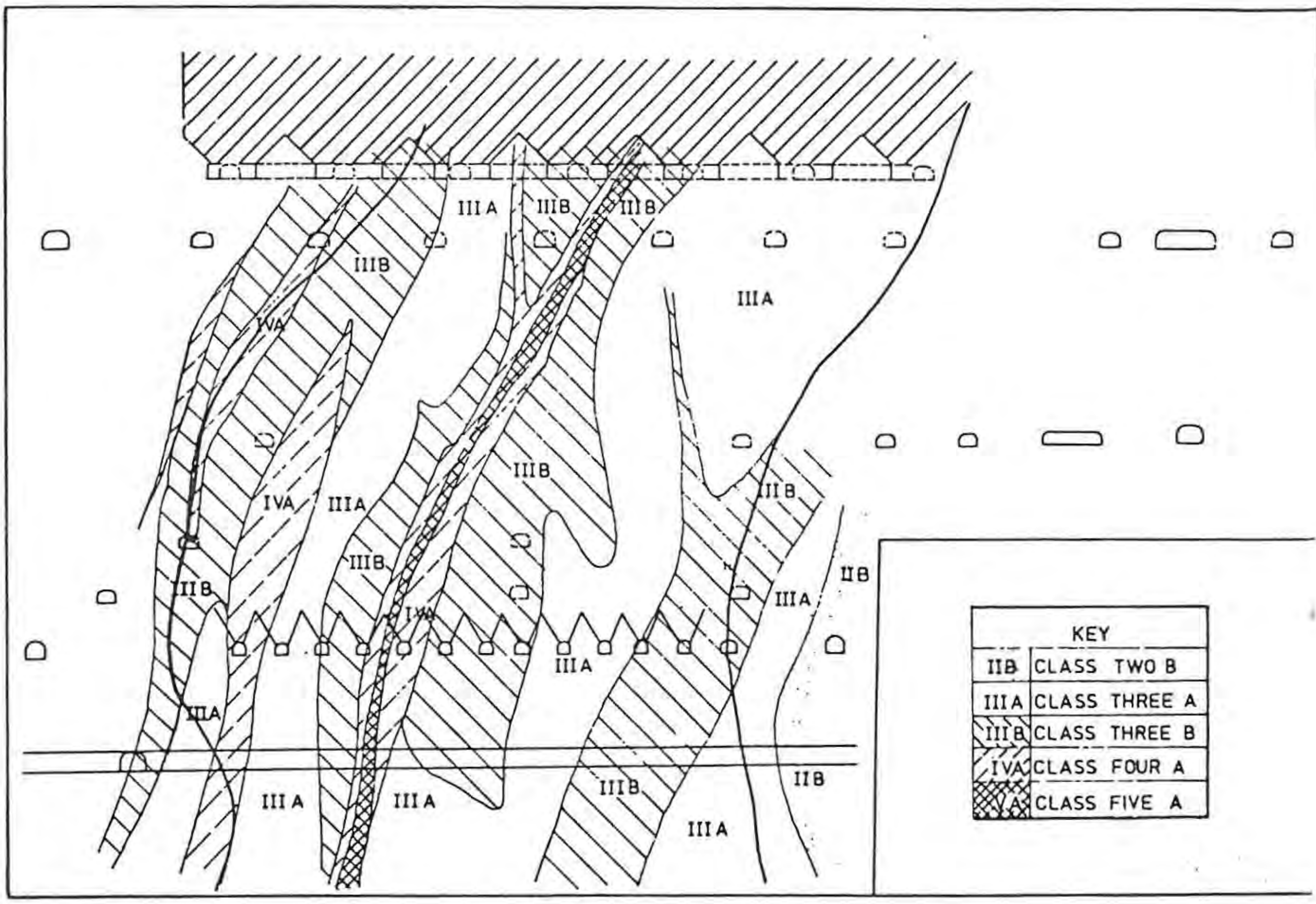


Figure 7.4: Cross section through 2/3 - 3/3 blocks King Mine showing classification data. (Laubscher, 1980 a)

As most serpentinite bodies deform in the plastic to elasto-plastic range and three-dimensional assessment is needed, mathematical models and analogues based on elastic theory have limitations but are helpful in determining stress concentrations before failure. The extent of the failure zone surrounding a mining (stoping) excavation will be directly related to the magnitude, ratio and stress changes during the stoping operation, as well as the strength of the rock mass (in-situ rock mass classification). Where high stress concentrations exist in the back of an excavation, the effect of adjustment displacements along joints is more dramatic, as gravity plays a significant part.

It must be remembered that a new undocumented stress environment is created as the mining operation expands. Therefore predictions must be based on the geological environment, the redistributed stresses, experience from broadly similar deposits, the monitoring of ground response to date, as well as the orientation and shape of the proposed excavation.

Mining Methods

Most mines began life as surface quarries and eventually converted to underground operations as the overburden/ore ratio increased beyond economic limits, or as sub-out-cropping bodies were discovered. These operations are almost invariably large-scale and fairly highly mechanized with long-hole bench blasting, front-end loaders and/or crowd shovels with dumper or lorry haulage.

Various underground mining methods have been adopted to suit the conditions of the particular circumstances; different methods are often used at one mine to suit particular orebodies or parts of them. The following methods have been used to varying extents:

(a) Cut and fill
(b) Shrinkage
(c) Sub-level open stoping
(d) Block caving
(e) Sub-level caving
(f) Room and pillar stoping

Support systems and their design are described by Ferguson (1977), and installation techniques are also well documented. Important factors which affect the selection of the support system are joint spacing, condition and orientation, and the presence of shear zones and weathering. If the rock mass classification is known no problems should be experienced during the development stage. However, it is in the support of the rock mass in the dynamic stress environment caused by the mining operation that support problems really become significant.

In the studying of underground mining methods, the following must be considered:

1) Geometry - massive spherical, massive tabular, narrow tabular, lenticular - continuous or disconnected.

2) Labour - sophisticated or unsophisticated, plentiful or at a premium.

3) Lashing or ore - mechanised or manual, dependent on skills available and availability of equipment and spares.

4) Preliminary orebody specification.

5) Preliminary rock mechanics assessment.

6) Production requirements versus production potential.

A short list of mining methods can be prepared. Initial planning and preparation of layouts will soon indicate where more detailed investigations are required, for example, extra drilling to determine ground conditions.

As most chrysotile asbestos deposits are massive with fairly low currency value, the large tonnage methods employed fall into caving and non-caving categories.

In caving, the ground overlying the orebody caves or subsides as the ore is drawn through drawpoints or loaded from extraction points. The ore itself can be (a) undercut and allowed to cave, or (b) primary-broken and loaded on sub-levels, or (c) shrunk through drawpoints. Whether the ore is caved or primary-broken will depend on the fragmentation, which is determined by the rock mass classification. The term "block caving" is used to describe an ore caving operation, whether by blocks or panel retreat, based on failure of the undercut mass. Two forms are recognised: stress caving occurs when sloughing takes place from the back, and the cave progresses upwards with the size of the area undercut to initiate the cave depending on the ratio of the stress, the rock mass strength and the orientation of the joints; subsidence caving occurs (a) when previous mining has removed lateral restraint and there is a rapid fall of blocks with limited bulking, or (b) when the rate of undercutting exceeds the rate of failure of the back until this fails en masse, possibly with an air blast (Heslop, 1976). The rate of undercutting should be such that it is slower than the failure of the back but faster than the failure of the extraction horizon caused by high abutment stresses.

Poor fragmentation causes numerous problems in block caving, namely high secondary blasting costs, blasting damage to brows, hangups which affect productivity and damage major apices, high dilution and ore losses. Although stress caving will mean better fragmentation than with subsidence caving, it only occurs at the start of a cave mining operation or in the caving of isolated blocks.

The fragmentation of the overburden rock mass is also important as it can influence dilution. Geological investigation to determine the caveability and fragmentation of the orebody must extend into the hangingwall for at least the height of the orebody. The mining block size must allow the caving of the hangingwall to follow the caving of the ore. This applies particularly to sub-level caving operations or primary breaking operations which require the hangingwall to cave. The potential cave area should be drilled, and instrumented with clamps or caving indicators, so that caving can be monitored and draw rate controlled.

Sub-level caving is extremely well-documented but unfortunately, as most mining men have found, the claims for the method are more optimistic than factual. So much so that the Swedes have proposed a modification to improve ore extraction and decrease dilution. This "new mining method" was introduced on Shabanie Mine some ten years ago to help solve the above problems.

A major problem with sub-level caving asbestos orebodies is that a large percentage of the mineral reports in the fines, so that loss of fines means a high extraction loss. These fines enrich the dilution zone, and extensive overdraw takes place on the lower levels resulting in a low mill yield. Sub-level caving of the Shabanie deposits was described by McMurray (1976). If its limitations are accepted, sub-level caving can be used where it is not possible to block cave, sub-level shrink or open stope, provided the ground is sufficiently competent that excessive support is not needed. A well developed shear zone in the immediate footwall of a dipping orebody will mean various problems for any footwall extraction layout or horizontal layout if drifts have to tranverse it. With high draw columns, wedges form against the shear and move downwards as the lateral restraint is removed and high stresses develop at the apex (toe) of the wedge. If the shear zone is straight, the orebody can be sub-level caved on a strike retreat with the end nearest the shear zone leading. If the hangingwall is competent, the retreat can be from footwall to hangingwall. Because of the numerous weak joints in chrysotile deposits, the lead between levels and between faces and the orientation of the sub-level drifts must be carefully planned, otherwise moving blocks of ground will cause loss of holes and support problems. Level-by-level extraction is often the most advisable as angles of influence can be extremely low. Potentially unstable wedges must not be allowed to form, and it may be necessary to break waste, particularly with a footwall-to-hangingwall retreat. As ground failure is often time-dependent, a steady retreat must be maintained.

Shrinkage with drawpoints is used when fragmentation is such that block caving will mean low productivity, high secondary blasting costs and damage to the extraction level. The rock mass strength classification will determine the technique employed to break the ground. In an inhomogeneous rock mass, if the more competent zones can be defined, it is logical to break those only. Mass blasts with large-diameter, widely spaced holes can be used. If the swell is drawn through drawpoints, sub-level shrinkage by ring drilling works effectively; if drawn on the sub-levels, there is a tendency to overdraw and introduce early dilution. It is essential that the hanging wall caves, and therefore only a limited tonnage can be drawn until the cave is established, causing a tie-up of ore for some time.

Open stoping methods have been successfully employed on Shabanie Mine, where the surrounding rock mass has a class 2 rating, favourable joint orientation, and the stress level did not exceed 20 MPa. However, at higher stress levels failure along unfavourably orientated joints takes place, and the stability of both pillars and back is affected, that is, the in-situ rating of, say, 70 is adjusted to 45. The shape of the open stope, with respect to the principal stress directions, is also significant. These factors must be taken into consideration in designing an open-stope method.

Room and pillar stoping methods are used in the crocidolite fields of the northern Cape where stoping widths vary between 1,2 and 12 metres, mining along strike of the fibre bands. The hangingwall conditions are good due to the natural parting and competent nature of individual bands in the iron formation. The maximum stable span between the 3 x 3 m pillars is 6 m so that about 8-9% of the ore is left as pillars. In zones of folding the hangingwall is not as competent and therefore the span between the pillars is reduced. Minor roll structures occasionally cause some problems in the mining, as do north-south trending faults that cause local horst and graben displacement. Infill underground diamond drilling is used to delineate the reef in these areas of structural disturbance. As major monoclinal flexures effect the dip of the ore zone, careful control of the hanging and footwall contacts has to be maintained. Mining at right angles to these rolls results in a minimum of overbreak and resultant dilution of the ore. The fibre bands are developed parallel to the bedding in the Iron Formation, therefore marker horizons can be used to keep the stope on the ore zone that was initially defined by sampling. The natural partings along the bedding planes enables the stope face to be kept with ± 10 cm of a particular marker band. Some of the fibre is damaged during the blasting and scraping.

Similar methods are used in the amosite field of the northeastern Transvaal, where the main reef at Penge is about 135 cm with a dip of about 20° southwestwards. A sloping face is advanced along strike, with the broken material formerly hand sorted underground as the main fibre-bearing reef commonly contains up to 30 percent asbestos. Sorting is now done on surface as previously excessive values were left behind in the temporary pillars used for roof support.

Grade Control

At Msauli (E. Sutton, pers. comm., 1982) the grade of the orebodies are carefully monitored to produce a constant run-of-mine grade. The percentage fibre and fibre length distribution are important controlling factors of the ore grade. The grade control samples are taken at 3 m intervals on either side of each crosscut through the ore zones and each sample processed in the pilot plant adjacent to the mills. The sample values are combined into units corresponding to two ring blasts. Blasted rings from different mining ends are then combined to produce a constant run-of-mine ore.

The crosscut sampling method tends to underevaluate the in situ ore grade percentages as, during cutting of the rock, fibre-bearing fragments tend to break away and are lost to that sample. This sampling method does not therefore compare directly to borehole core samples and run-of-mill grade. However, with fragmentation of the fibre due to blasting and several handling sequences, the crosscut channel samples may be reasonably representative of the eventual mill head grades.

In the crocidolite mines, grade control is maintained by similar visual methods to that used in exploratory core estimations. All fibre seams in excess of 3 mm are expressed as a percentage over the total mined width. During the mining operations the stope faces are usually sampled at 6 metre intervals but as the grade is more variable in folded areas the faces are sampled every 3 metres. However, the estimated grade, which is a volume percent, does not correspond to the actual grade processed by the plant, which is a weight percent, because the constant S.G. factor of 3,375 is used for tonnage estimates even though the S.G. of the ore is variable. Fairly large losses of fibre are, however, incurred in the handling and processing of the ore, with generally only between 55 and 65% of the total in situ calculated reserves being recovered.

Over-drawing beyond the economic limit continues to be a major problem in any caving operation on asbestos mines, invariably leading to mill yields lower than forecast. Generally non-uniform distribution of fibre values and creation of fines during mining means that visually assessing or sampling asbestos orebody drawpoints is more difficult than encountered in drawpoints of orebodies with disseminated mineralization.

Visual assessment of drawpoints and extraction points is difficult and inaccurate, and where necessary, should be attempted only by those qualified to do so. Unfortunately, when other sources of ore are not available, drawpoint assessments tend to be optimistic. The following factors must be taken into consideration when visually assessing extraction points:

In-situ values. The value distribution, the length distribution, the seam pattern of both the orebody and the dilution zone must be known. Where values decrease towards the hangingwall contact a wide marginal ore zone cannot tolerate high dilution. Erratic distribution of values in dilution zones can result in bad assessment, owing to attention being focused on a large rock containing several fibre seams, to the exclusion of barren rocks. High-grade ore can be in contact with the dilution zone, so that the ore can tolerate a high dilution.

Host rock and serpentinization. Chrysotile asbestos occurs in partially serpentinized dunite and serpentinite. In the former, fibre seams are always bounded by serpentine and the degree of serpentinization will usually be related to the fibre content. If the fibre is loose in the seam, the serpentine content of the rock will indicate whether it originated from a fibre zone or a barren zone.

Fines. The fibre in the fines can be spelky or highly opened. The highly opened fibre makes the fines look impressive but in fact is of a lower value than spelky fibre. High value spelky fines can run at 15 per cent fibre content, whereas opened fines would have values of 5 per cent. If the fines constitute 10 per cent of the tonnage this would mean fibre contents of 1,5 per cent or 0,5 per cent respectively.

Laubscher (1980 b) comprehensively describes the grade control facets including bulk sampling, and grade control graphs from which cut-off values, cube valuation and calculated tonnages can be obtained, as well as the problem of dilution. It is not in the scope of this review to detail all these facets.

GEOLOGICAL FACTORS AFFECTING EXTRACTION

Extraction methods have been described in great detail by Winson (1975) and Mann (1981), including flow sheet diagrams. Numerous other writers have described extrapolation techniques, mineralogical and chemical contaminants in milled fibre including: Caouette et al. (1971), Monkman (1975), Reimschussel (1975) and Hirner (1980).

Milling

In milling, the extracting of asbestos fibres from the ore is generally a dry mechanical process involving crushing to dissociate the asbestos and the host rock, followed by screening and air lifting to separate the factions. During this process, and after, the fibre itself is separated into various ranges of size so that various grades of fibre are produced. The factors affecting the milling of chrysotile are:

a) moisture content of the ore : fibre can only be milled when dry.

b) host rock characteristics : whether soft and granular or tough and compact.

c) quality of the fibre : whether soft and silky or harsh and brittle. This affects the degree of fiberization of the fibre.

d) nature of the fibre : kinks reduce fibre length while crenulations increase fibre cohesion, making fiberization more difficult.

e) sidewall adhesion : host rock adhesion may be low allowing free milling of the fibre, permitting the early rejection of waste rock. High adhesion requires further costly milling of the ore before fibre is separated from the host rock.

f) high value of long spinning fibres : separate milling treatment is required for this type.

g) the accepted classification and grading to specified standards : the fibre in some instances has to be degraded to meet these specifications.

The last factor lowers the grade and increases fibre quantity as compared to higher grades and lower percentage fibre obtained when estimated visually by borehole core and in situ sidewall methods.

Primary and secondary crushing is conventional, jaw and cone crushers being used. If necessary, the ore will be dried either between the stages of crushing or after secondary crushing.

This is followed by a sequence of trommels, tables, rotaries and air lifts, each stage being followed by Johns-Manville fiberizers, jumbos or hammer mills until the fibre content is freed from the rock, or until the remaining recoverable fibre would be insufficient to justify a further stage of milling. The fibre is drawn off by air lifts and delivered to cyclones which feed the asbestos with some entrapped grit to the grading section.

Individual ores merit variations in the above simplified picture as, for example, the oversize after primary crushing may pass to a sorting belt where crude fibre and waste may be hand-picked. The hand-picked crude fibre may be sold separately in its unfiberized form. Wet milling has been used in the recovery of "shorts" from mill tailings.

At Msauli (B. Reed, pers. comm., 1982) the ore is crushed to liberate the fibre and then hammered to fiberize it. Once fiberized the high surface area : mass ratio of the asbestos enables the fibre to be separated from the silicate, magnetite and host rock gangue by a process of air lifting. Several dedusting cycles remove all unwanted grit from the fibre through vigorous air activation within closed cyclones. Fibre length of the asbestos is critical which requires hammering and separation of longer fibres before they become damaged. A sequence of seven stages of hammering is done with the removal of each length of fibre collected by screens of a specific mesh size before the fibre is hammered again.

The brittle nature of the antigorite and slip-fibre produces poor fiberization which allows relatively good separation of the cross fibre from the gangue. The host rock is easily separated as there is usually a very thin magnetite layer between the fibre and seam wall which prevents fibre adhering to the host rock during crushing. The ore must be dry before hammering as it will not fiberize if wet. A vertical downdraft coal fired drier dries the ore by heating the rock to 30°C before crushing.

Beneficiation of crocidolite fibre is initially by hand sorting which upgrades the ore from 6 to 18 percent. The ore is crushed and screened into two size fractions, -38 + 18 mm and -18 + 3 mm. The -3 mm material is discarded onto the waste dump. The fibre length of the asbestos is important so that it is necessary to separate the coarse blocks with larger fibre from the shorter fibre. The separation is efficient because the ore tends to have natural parting close to the edges of the fibre bands. The ore is hammered to fiberize the asbestos. The high surface area to weight ratio of the asbestos enables it to be airlifted from the silicate and magnetite gangue. Some of the asbestos breaks along kink bands in the hammer mills so that the proportion of long to short fibre in the product differs from that estimated during sampling. The airlifted fibre is degritted and dedusted to remove the fines. A maximum of 1,5% dust is permitted in the final product.

Fibre Grade Evaluation

Cossette and Delvaux (1979) describe the evaluation of the fibre grade in detail. The grade of the fibre is determined by the Quebec Standard Testing Machine in Canada and by similar methods in the other producing countries. Three boxes, with mesh screens at their bases of 2,4 and 10 mesh openings respectively, are superimposed above a pan, which is the lowest box. A 16-ounce sample is spread out on the top box, is covered, clamped and, by eccentric motion, is shaken for 600 revolutions. The weights of the fractions from each box are compared with the minimum specifications (Table A1 in Appendix) and the grade of the fibre can be established. The currency value of this grade can be obtained from current price lists, with long fibre grades commanding the highest prices.

The grade and value of the fibre is directly comparable to the amount of long fibre retained by the first screen.

Once the grade and currency value of the fibre in a given orebody has been determined, and if this value is significant enough to warrant additional consideration, then it becomes imperative to evaluate the inherent fibre characteristics to ascertain the market to which this fibre may be suitable. Visual and manual inspection can yield valuable information on the fibre characteristics to the experienced evaluator. However, several fibre characteristics cannot be estimated by inspection, and these must be determined by using standardized methods of test to obtain data that can be compared with the standard data that is available.

The quality of the fibre is dependent upon numerous geological factors which may affect the inherent physical and chemical properties of the fibre. These properties have already been described and are tabulated in Table 1.3.

The fibre grade evaluation includes : fibre length distribution; degree of fiberization; strength imparting properties; cleanliness and associated mineral impurities; moisture content; and miscellaneaous properties. Cossette and Delvaux (1979) describe these tests in detail.

Some examples of the geological factors which affect fibre grade are :

tensile strength: cross fibre has higher strength than slip fibre, which affects its reinforcing use.

colour: slight discoloration may be significant enough to restrict market applications, especially for fillers.

acid resistance: white fibre implies a high brucite content, which reduces the fibre acid resistance.

Badollet (1969) comprehensively describes physical properties and technical applications of asbestos minerals, including amphibole fibres.

Classification of Fibre Grades

The determination of the grade of fibres obtained by milling is based upon the Canadian chrysotile asbestos classification established in 1931 by the Committee on Uniform Classification and Grading of Asbestos Mines Products.

In Canada the recognized classification is known as the Quebec Standard Test (Q.S.T.), which is used as a production control and serves as a specification of the grade for fibre marketing. Chrysotile fibre producers in southern Africa, Russia and Australia, and the amphibole asbestos producers of South Africa have evolved their own testing methods for grading and classifying fibres, but do use the Q.S.T. as a basis.

The classifications of the fibre grades of the asbestos producers are tabulated in the Appendix (A6 - A7).

The many uses for asbestos fibres are listed in the Appendix (A8 - A9), reproduced in its entirety from Winson (1975). The markets accessible to a particular fibre class are of paramount importance in the decision making process involved in the assessment of a fundamental value to that asbestos fibre. This is of prime importance in deciding upon the feasibility of profitably exploiting an unknown asbestos orebody.

CONCLUSIONS

The main controlling factors in the formation of economic deposits of chrysotile asbestos are:

Host-rock control. In general, fibre seams are confined to those rocks that (a) have the same composition as the chrysotile fibres, i.e. the green serpentinites, and (b) consist predominantly of dunites and peridotites. These rocks will readily provide magnesium and silica for fibre growth, or will recrystallize to fibre in situ.

Serpentinous solutions. This term denotes a solution containing magnesium and silica, from which serpentine minerals can form. The serpentinization of olivine by hydrothermal solutions causes excess magnesium and silica to form the serpentinous solution. Therefore in partially serpentinized dunite, as at Shabanie and Gath's Mines, hydrothermal solutions were essential. In the serpentinites, e.g. King Mine, the serpentine appears to have dissolved in areas of pressure, assisted by hydrothermal solutions.

Structural control. The main features in structural control are:

a) formation of fractures in which stress-controlled dilation seams can form and from which serpentinization can occur. The fractures might pre-date the major structures in the area, e.g. Shabanie, or be contemporaneous, e.g. King.

b) The development of thrust-faults, wrench-faults and shear-zones, which would act as channels for hydrothermal solutions or have areas of pressure where serpentine could dissolve, and with associated areas with minor principal stress direction suitably orientated for the formation of stress-controlled dilation seams. Significantly, fibre is best developed in areas with the simplest structural pattern.

c) In areas where wrench-faulting was dominant, slip-fibre is localised in the fault-zone or sympathetic structures.

d) Structures creating the correct stress environment for serpentine minerals to recrystallize into fibre seams.

There appears to be three fundamental controls to crocidolite fibre development:

1) only parts of the basin contain crocidolite where sodic brines were present, so that large areas are barren;

2) stratigraphic control is marked, and depends on layers amenable to replacement (Trendall and Blockley, 1970) and horizons that are relatively permeable (Grubb, 1971);

3) structural control is important, and depends on the presence of low-stress environments (Trendall and Blockley, 1970; Grubb, 1971) in the axial zone of folds (Cilliers and Genis, 1964; Hanekom, 1966; Fockema, 1967, Dreyer and Robinson, 1978) and in dilatant sites formed by opposing stresses (Trendall and Blockley, 1970). Logically, structure would also be expected to be important in the way in which it affected migration of the sodic brines.

Amosite-bearing iron formation occupies a fairly unique stratigraphic position, in that it sub-outcrops beneath the pre-Pretoria Group unconformity. It is thought that circulating groundwaters operative during the era of pre-Pretoria weathering may have leached the soda from the proto-riebeckite, leaving amosite as the recrystallized leached product.

APPENDIX

A1 Major world asbestos producers (Clarke, 1982)

Company	*Ownership*	*Mine/plant location*	*Products/capacity*	*Remarks*
THE AMERICAS				
Canada				
Asbestos Corporation Ltd.	General Dynamics Canada Ltd. — 54.65%.	King-Beaver open pit, Thetford Mines, Quebec	All chrysotile 2.1m. tpa of ore	Total chrysotile fibre production capacity — 292,300 tpa
	Through Société Nationale de l'Amiante the Quebec government has purchased 51% of the voting shares in GDC	Normandie mill, Vimy Ridge, Quebec	83,800 tpa of fibre Groups 3-7	Group 3 — 4,100 tpa Group 4 — 162,000 tpa Group 5 — 73,300 tpa Group 6 — 29,400 tpa Group 7 — 23,500 tpa
		King-Beaver u/g mine, Thetford Mines, Quebec	1.1m. tpa of ore	
		Brit. Can. mill No.1, Black Lake, Quebec	54,700 tpa of fibre Groups 3-6	Predominantly used for asbestos cement but also textiles (Group 3 only), brake linings, tiles, paper, gaskets, and filler
		Brit. Can. open pit, Black Lake, Quebec	3.2m. tpa of ore	
		Brit. Can. mill No.2, Black Lake, Quebec	65,300 tpa of fibre Groups 3-7	
		Asbestos Hill open pit, Ungava, Quebec	1.4m. tpa of ore. 265,000 tpa ungraded fibre	All shipped via Deception Bay to Nordenham, West Germany
Asbestos Corporation GmbH	Wholly-owned subsidiary in West Germany	Nordenham mill, West Germany	Chrysotile 88,500 tpa of fibre. Groups 4-7	All used for asbestos cement
Bell Asbestos Mines Ltd.	Société Nationale de l'Amiante (acquired from Turner and Newall Ltd. in May 1980)	Underground mine and mill in Thetford Mines, Quebec	Chrysotile 825,000 tpa of ore. 75,000 tpa of fibre Groups 3-7	Specialise in output of longer fibres 70% Groups 3-5 and 30% Groups 6-7
Brinco Mining Ltd. (newly formed early 1981)	Olympia and York Investments Ltd. (50.1%) and Rio Tinto Zinc Corp. (22%) in Brinco Ltd. the direct parent company	Cassiar open pit and mill, McDame Mountain, north-central British Columbia	Chrysotile 1.3m. tpa of ore. 110,000 tpa of fibre Groups 3-6	Primarily Group 4 fibre produced, 70% of output for asbestos cement. Mine acquired from Cassiar-Asbestos Corp. in 1980
Carey Canada Inc.	Jim Walter Corporation	Open pit and mill at East Broughton Station, Quebec	Chrysotile 225,000 tpa of fibre. Groups 4-7	Specialises in medium to short fibre — 70% Group 7 and 30% Groups 4-6. Maximum output of 234,000 tonnes in 1973
Johns-Manville Canada Inc.	Manville Corporation	Jeffrey open pit and 6 mill complex at Asbestos, Quebec	Chrysotile 9.25m. tpa of ore 630,000 tpa of fibre Groups 3-7	Western World's largest asbestos mining operation
Lac d'Amiante du Quebec Ltée	Asarco Inc.	Black Lake open pit and mill, Black Lake, Quebec	Chrysotile 13,600 tpd of ore 165,000 tpa of fibre Groups 3-6	Mined under a 99-year lease from United Asbestos Inc. in return for share in net profits
			National open pit and mill, near Thetford Mines, Quebec	7,260 tpd of ore 100,000 tpa of fibre Principally Group 7
USA				
Calaveras Asbestos Corporation	—	Open pit mine and mill at Copperopolis, California	Chrysotile 3,600 tpd of ore 40,000 tpa of fibre Groups 4-6	Leading producer of asbestos in the USA and one of few mines to have expanded production in recent years
Union Carbide Corporation		Open pit mine and mill at Santa Rita, San Benito County, California	Chrysotile 35,000 tpa of fibre Group 7 mainly	Specialises in short fibres and modified asbestos products for filler reinforcing applications
Vermont Asbestos Group	Cooperative	Open pit mine and mill at Lowell, Vermont	Chrysotile 35,000 tpa of fibre Groups 3-8 1.1m. tpa of ore	Current production is around 23,000 tpa of fibre
The Jaquays Mining Corp.	—	Open pit mine and mill in Gila County, Arizona	Chrysotile 1,200 tpa of fibre Groups 3, 4 and 7	
Brazil				
SA Mineraçao de Amianto	—	Cana Brava mine and mill, Uruaçu, Goiás state	Chrysotile 180,000 tpa of fibre Grades 3-7	Only recent attempts to enter world trade. Some 167,000 tonnes produced in 1980

A2

Company	*Ownership*	*Mine/plant location*	*Products/capacity*	*Remarks*
Sano SA Industria e Comercio	Sano Group	Mine and mill in Piaui state	Chrysotile 2,400 tpa of fibre Group 4 only	Production totally consumed within the Sano Group
Colombia				
Asbestos Colombianos SA	Eternit Colombiana 70% Minero Emmo 30%	Las Brisas mine and mill, near Campamento	Chrysotile 20,000 tpa of fibre Groups 4-6	Production began during 1981 at initial rate of 11,000 tpa
AFRICA				
South Africa				
The Griqualand Exploration and Finance Company Ltd. (Gefco)	General Mining Union Corporation Ltd. 43.80% Sentrust Ltd. 13.16%	Elcor mines, mill and blending plant, Kuruman district, North Cape Province	Crocidolite 48,000 tpa of fibre	Wholly-owned Elcor Investments, through its Merencor Asbestos Mines (Pty) Ltd. and Coretsi Asbestos (Pty) Ltd. owns operating mines at Eldoret and Coretsi in the Kuruman district
		Riries blending plant supported by Asbes, Bretby, and Riries mills taking ore from a number of small mines	Crocidolite 32,000 tpa of fibre Elcor and Riries blending plants produce 4 grades of crocidolite — long, medium-long, medium, and medium short (5mm to 25mm)	Wholly-owned Griqualand Asbestos (Pty) Ltd. works an asbestos mine near Kuruman and its subsidiary Griqualand Chrysotile Mines (Pty) Ltd. bought the Bute mine near Vryburg from Dublin Consolidated Asbestos Mnes (Pty) Ltd.
		Whitebank mine and mill supplying the Central blending plant, Cape Province	Crocidolite 30,000 tpa of fibre	Whitebank and Klipfontein operations recently acquired from Asbestos Investments, a subsidiary of the Belgium-based Eternit group, which operated under the name Kuruman Cape Blue Asbestos (Pty) Ltd.
		Klipfontein mine and mill supplying the Owendale blending plant, Cape Province	Crocidolite 18,000 tpa of fibre	
		Pomfret mine, mill, and blending plant, northern Cape Province	Crocidolite 70,000 tpa of fibre	Pomfret and Penge operations recently acquired from Transvaal Consolidated Land and Exploration Co. Ltd.
		Penge mine, mill, and blending plant, eastern Transvaal	Amosite 90,000 tpa of fibre	These mines were respectively operated by Cape Blue Mines Ltd. and Egnep Ltd.
Msauli Asbestos Ltd.	General Mining Union Corporation Ltd.	Msauli mine, mill, and blending plant, Msauli, Barberton district, eastern Transvaal	Chrysotile 100,000 tpa of fibre Groups 5-7 but mainly Group 6	African Chrysotile Asbestos Corporation is Gencor's wholly-owned holding company for Msauli Asbestos
Duiker Exploration Ltd.	Lonrho Ltd.	Wandrag mine and mill, Kuruman district, Cape Province	Crocidolite 9,000 tpa of fibre	
		Emmarentia mine and mill, Cape Province	Crocidolite 1,000 tpa of fibre	
Kaapsehoop Asbestos (Pty) Ltd.	—	Mine at Joubertsdal in Nelspruit district	Chrysotile 10,000 tpa of fibre Grades 3, 4T, 5R	Small independent operation with sales by Southern Asbestos Sales (Pty) Ltd.
Anglo Dutch Exploration and Mining Co. (Pty) Ltd.	—	Stella mine near Kaapsehoop in Nelspruit District	Chrysotile 4,200 tpa of fibre Grades 6D and shorter	Small operation for local market — friction materials, paints, floor tiles, filtration
Zimbabwe				
Shabanie and Mashaba (Pvt) Ltd. (SMM)	Turner and Newall Ltd.	Shabanie mine and mill, Shabanie, Victoria	Chrysotile 2.4m. tpa of ore	Combined chrysotile production capacity is around 250/300,000 tpa of fibre. Production predominantly comprises Groups 3 and 4 grades of fibre. Approximately 50% of world textile asbestos fibre comes from these mines
		Gaths mine and Temeraire mill, Mashaba, Victoria	2.44m. tpa of ore	
		King mine and mill, Mashaba, Victoria		
DSO Asbestos (Pvt) Ltd.	Industrial Development Corporation	Mashaba, Victoria	Chrysotile 6,000 tpa of fibre Groups 4 and 5	Underground mining ceased in 1978. Current output is based on ore dumps from SMM

A3

Company	*Ownership*	*Mine/plant location*	*Products/capacity*	*Remarks*
Swaziland				
Havelock Asbestos Mines (Swaziland) Ltd.	Turner and Newall Ltd. 60%, Swaziland government 40%	Mine and mill at Bulembu, northwest Swaziland	Chrysotile 35,000 tpa of fibre High proportion of Groups 3 and 4 plus some shorter fibre	Milled fibre product is sent via 22 km long cable to South Africa Barberton and exports sent through Maputo or Durban

EUROPE

Company	*Ownership*	*Mine/plant location*	*Products/capacity*	*Remarks*
Italy				
Amiantifera di Balangero SpA	Eternit Group of Switzerland	The Balangero open pit and mill, San Vittore, northwest of Turin	Chrysotile 200,000 tpa of fibre Groups 4-7	Leading producer of asbestos in Europe
Greece				
Asbestos Mines of Northern Greece SA	Hellenic Industrial Development Bank (ETBA) 91.5%, IFC 8.5%	Mine and mill at Zidani, south of Kozani town	Chrysotile 5m. tpa of ore 100,000 tpa of fibre Groups 4-7	Finally started production in late 1981 and expect to produce 75,000 tonnes in 1982 of which 29% will be sold in Greece
Cyprus				
The Cyprus Asbestos Mines Ltd	—	Open pit mine and mill at Pano Amiandos in the Troodos Mountains	Chrysotile 35,000 tpa of fibre Groups 4-7 but mainly 4 and 5	Production in 1980 was 34,000 tonnes and about 27,000 tonnes in 1981
Yugoslavia				
Mines and Industry of Asbestos-Chemical Products "Jugoazbest"	State	The Korlace mine	Chrysotile 4,000 tpa of fibre	Mine undergoing reconstruction to increase output to 12,500 tpa
Stragari Asbest mine	State	Operation located at Bogutoyo, Stragari, Serbia	Chrysotile 15,000 tpa of fibre	
Turkey				
Bilfer Maden Ltd.	Bilgin Group	Cavdar mine, Sivas, eastern Turkey	Chrysotile 1,500 tpa of fibre Groups 4-7	Essentially a pilot plant operation being increased to 5,000 tpa during 1982 to supply domestic asbestos cement market. By 1984 Bilfer hopes to start on a 80-100,000 tpa project. Production to date — 300 tons
Amyant Sanayi AS	Unimeks Yatirim ve Finansman AS	Mine and mill at Mihalliççik Tatarcik, Eskişehir	Tremolite asbestos 30,000 tpa of ore 3,000 tpa of fibre Groups 5-7	Current production is around one third capacity for floor covering, adhesives, and insulation

ASIA

Company	*Ownership*	*Mine/plant location*	*Products/capacity*	*Remarks*
India				
Hyderabad Asbestos Cement Products Ltd.	—	Mine and mill at Roro, Bihar state	Chrysotile 2,000 tpa of fibre Groups 5-7	Supply domestic market and manufactures asbestos cement products
Pratap Commercial Co. (Pvt) Ltd.	—	Nine mines in Udaipur and Beawer Districts of Rajasthan (open pit and underground)	Anthophyllite and tremolite asbestos 4,000 tpa of fibre Equivalent to Groups 4-7	Output in 1980 approximately 2,500 tonnes
South Korea		Kwangchon and Hongsong mines, Hongsong-gun, 90 miles east of Seoul	Chrysotile 14,000 tpa of fibre Average 5mm in length	
Japan				
Nozawa Asbestos Cement Company	—	Furano, Hokkaido	Chrysotile 18,000 tpa Mainly short fibres	For asbestos cement production
Yamabe Asbestos Company Ltd.	—	Yamabe, Hokkaido	Chrysotile 4,500 tpa of fibre Groups 6-7	For asbestos cement production. Current output from Japanese mines is around 8,000 tpa
Australia				
Woodsreef Mines Ltd.	Transpacific Asbestos Inc. 58.57% (formerly Woodsreef Minerals Ltd. of Alberta, Canada)	Wood's Reef mine and mill, near Barraba, New South Wales	Chrysotile 95,000 tpa of fibre Groups 4-7	Operations are carried out by wholly-owned Chrysotile Corporation of Australia Pt Ltd. Output in 1980 — 83,466 tonnes

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Company	*Ownership*	*Mine/plant location*	*Products/capacity*	*Remarks*
USSR				
Uralasbest Combine	State	Asbest, about 30 miles east of Sverdlovsk in the south-central Urals. Mine and 6 mill complex	Chrysotile 1.56m. tpa of fibre Accounts for about 51% of Soviet capacity (reported to have lost 500,000 tpa capacity at 2 mills during 1980)	Construction of another mill with a reported capacity of 340,000 tpa is being planned. Output in 1980 — 1.27m. tonnes
Dzhetygara Combine	State	Dzhetygara, northwest Kazakhstan, about 300 miles south of Sverdlovsk in southern Urals	Chrysotile 750,000 tpa of fibre Accounts for about 25% of Soviet capacity	Two mills in operation — the first built in 1965 with 350,000 tpa capacity and the second built 1975 with 400,000 tpa capacity. Output in 1980 — 640,000 tonnes
Kiembay Combine	State in conjunction with 33% financial participation from Bulgaria, Hungary, East Germany, Poland, Rumania, and Czechoslovakia	Located about 90 miles east-south-east of Orsk in Orenburg Province in the southern Urals	Chrysotile 500,000 tpa of fibre Accounts for about 16% of Soviet capacity	Two mills recently built, the first in 1979 which produced 130,000 tonnes in 1980 and the second was completed at end of 1980. 12 annual instalments of 170,000 tonnes to be sent to the 6 participating nations, and possibly for a further 10 years
Tuvaasbest Combine	State	Located near Ak-Dovurak in south-central	Chrysotile 240,000 tpa of fibre Accounts for about 8% of Soviet capacity	Two mills with equal capcity of 120,000 tpa each constructed in 1964 and 1976. Output in 1980 — 110,000 tonnes

China

The majority of Chinese chrysotile asbestos production is accounted for by nine mines of which the Shimien open pit and underground operation in Sichuan Province is the largest. Close to Shimien is another large deposit at Pengshien. The next largest mining area is in the district of Laiyuan, Hebei Province where open pit mining is carried out. Other mines are the open pit mine at Mangai, Quinghai Province; underground operations at Jinzhou and Chaoyong, Liaoning Province; open pit workings at Shennan in Shensi Province and underground and open pit operations at Lilang, also in Shensi Province. Another asbestos mine is worked at Taan in Shaanxi Province. Although production capacities of these various operations are not known total production of asbestos in China in 1980 was around 250,000 tonnes, all of which was apparently of the chrysotile variety.

A5

World production of asbestos *(tonnes)*

Country	*1975*	*1976*	*1977*	*1978*	*1979*	*1980*
Italy	146,984	164,788	149,327	135,401	143,931	157,794
Bulgaria	—	300	7,500	9,600	8,800	na
Czechoslovakia	—	—	—	575	564	617
Soviet Union	1,895,000	1,850,000	1,900,000	1,945,000	2,020,000	2,150,000
Turkey	15,496	9,941	3,975	13,380	38,967	8,724
Yugoslavia	12,336	12,830	9,036	10,304	9,959	12,106
Egypt	479	1,018	478	349	350	na
South Africa						
Amosite	88,411	78,893	66,983	40,526	39,058	57,646
Anthophyllite	1,912	1,506	550	—	—	—
Crocidolite	164,727	178,411	200,966	137,288	118,301	118,148
Chrysotile	99,660	111,025	111,575	79,511	91,828	106,940
Swaziland	37,610	39,327	38,046	36,951	34,294	32,833
Zimbabwe	261,542	281,455	273,194	248,861	2589,891	250,949
Canada	1,055,667	1,536,091	1,517,360	1,421,808	1,430,614	1,202,511
USA (a)	89,497	104,873	92,256	93,097	93,354	80,079
Argentina	1,130	889	686	697	700	-
Brazil	73,978	92,703	92,773	122,815	138,457	170,000
Afghanistan	—	13,260	13,000	13,000	4,000	na
China	150,000	175,000	200,000	230,000	250,000	250,000
Cyprus	31,602	34,518	36,684	34,359	35,472	35,535
India	20,312	24,119	22,177	24,623	32,094	31,253
Japan	4,612	7,703	6,307	5,746	3,362	na
Republic of Korea	4,345	4,762	6,180	13,616	14,804	9,854
Taiwan	1,737	853	673	2,031	2,957	683
Australia	47,922	60,642	50,601	62,744	79,721	83,466

(Clarke, 1982)

A6

SPECIFICATION

Group No. 1
No. 1 Crude-cross-fiber veins having 3/4-in. staple and longer.
Group No. 2
No. 2 Crude-cross-fiber veins having 3/8-in. staple up to 3/4-in. Run-of-Mine Crude consists of unsorted crudes. Sundry Crudes—consist of crudes other than above specified.

Group		Guaranteed Minimum Shipping Test			
		1/2 In., Oz	4 Mesh, Oz	10 Mesh, Oz	Pan, Oz
Group No. 3	(Commonly referred to as textile or shipping fibers				
3F		10.5	3.9	1.3	0.3
3K		7	7	1.5	0.5
3R		4	7	4	1
3T		2	8	4	2
3Z		1	9	4	2
Group No. 4	(Commonly referred to as asbestos cement fibers)				
4A		0	8	6	2
4D		0	7.0	6.0	3.0
4H		0	5	8	3
4J		0	5	7	4
4K		0	4	9	3
4M		0	4	8	4
4R		0	3	9	4
4T		0	2	10	4
4Z		0	1.5	9.5	5
Group No. 5	(Often referred to as paper stock grades)				
5D		0	0.5	10.5	5
5K		0	0	12	4
5M		0	0	11	5
5R		0	0	10	6
5Z		0	0	8.6	7.4
Group No. 6	(Paper and shingle fibers)				
6D		0	0	7	9
Group No. 7	(Shorts and floats)				
7D		0	0	5	11
7F		0	0	4	12
7H		0	0	3	13
7K		0	0	2	14
7M		0	0	1	15
7R		0	0	0	16
7T		0	0	0	16
7RF and 7TF Floats		0	0	0	16
7W		0	0	0	16
Group No. 8 & 9	(Sands and gravels)				
8S		0	0	0	16
		Minimum 50 lb per cu ft			
8T		0	0	0	16
		Minimum 75 lb per cu ft			
9T		0	0	0	16
		More than 75 lb per cu ft			

Table A1: Quebec grading as set by the Quebec Asbestos Mining Association (Winson,1975).

C-1	Crude 3/4-in. staple and longer.	
AAA	Extra long spinning fiber	– Canadian Group 3
AA	Long spinning fiber	– Canadian Group 3
A	Spinning fiber	– Canadian Group 3
AC	Spinning fiber	– Canadian Group 3
CC	Spinning fiber	– Canadian Group 3
AK	Asbestos-cement fiber	– Canadian Group 4
CP	Asbestos-cement fiber	– Canadian Group 4
AS	Asbestos-cement fiber	– Canadian Group 4
CT	Asbestos-cement fiber	– Canadian Group 4
AX	Asbestos-cement fiber	– Canadian Group 5
AY	Asbestos-cement fiber	– Canadian Group 5
CY	Asbestos-cement fiber	– Canadian Group 5
AZ	Asbestos-cement fiber	– Canadian Group 6
CZ	Asbestos-cement fiber	– Canadian Group 6

Table A2: Cassiar asbestos grades,northern British Columbia. (Winson,1975)

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C&G1 Long, crudy textile fiber C&G2 Textile fiber C&G3 Long shingle fiber C&G4 Shingle fiber C&G5 Short shingle fiber or paper stock	From mines in the Shabani district of Rhodesia
VRA-2 Textile fiber VRA-3 Long shingle fiber VRA-4 Shingle fiber	From the Mashaba district of Rhodesia
HVL2 Textile fiber HVL3 Long shingle fiber HVL4 Shingle fiber HVL5 Short shingle or paper stock	From the Havelock mine in Swaziland
Msauli – Grade 4 Msauli – Grade 5 Shingle fibers	From the Msauli mine near Swaziland border in the Transvaal
Amianthus 1 and 2 – Textile fibers F – Long shingle fiber AA – Shingle fiber	From the Barberton district of the Transvaal
Munnik-Myburgh M1 – Textile fiber M3 – Shingle fiber M4 – Short shingle fiber	From the Barberton district near Nelspruit of the Transvaal

Table A3: Classification of southern African chrysotile asbestos fibre (Winson,1975).

Grade	Type	Texture	Mark according to USSR Standards, 1972
0	Spinning fiber	Harsh, crudy	DV-0 80, DV-0 55
1	Spinning fiber	Harsh, crudy Semi-crudy	J-1-50, J-1-38 PRJ-1-75, PRJ-1-50
2	Spinning fiber	Harsh, crudy Semi-crudy Semi-open	J-2-20 PRJ-2-30, PRJ-2-15 P-2-30, P-2-15
3	Asbestos-cement fiber	Harsh, crudy Semi-open	J-3-40 P-3-70, P-3-60, P-3-50 M-3-70, M-3-60
4	Asbestos-cement fiber	Semi-open Open, soft	P-4-40, P-4-30, P-4-20, P-4-5 M-4-40, M-4-30, M-4-20, M-4-5
5	Paper fiber	Semi-open Open, soft	P-5-67, P-5-65, P-5-52, P-5-50 M-5-65, M-5-50
6	Paper and shingle Fiber and shorts	Semi-open Open, soft	P-6-45, P-6-30 M-6-40, M-6-30 K-6-45, K-6-30, K-6-20, K-6-5
7	Unguaranteed		7-300 7-370 7-450 7-520

Table A4: Classification of Russian chrysotile asbestos fibre(condensed). (Winson,1975).

Grade	Approximate Range Average Fiber Length, In.
S 11	1–1 1/2
W 3	1/2–1 1/2
K 3	1/2–1 1/2
SK	3/16–3/4
S 33	1/8–1/2
S 33/65	1/8–1/2
GW	1/8–1/4
GK	1/8–1/4
S 44	1/8–1/4
RK	1/8–1/4
6605	1/16–1/8

The grades listed above are produced in the Penge area from the Penge mine and the Weltevreden and Kromellenboog mines. The fiber lengths shown are not necessarily exact, but have been included in order to give some indication of the relative lengths of fibers of the different grades.

Table A5: Classification of South African amosite asbestos fibre (Winson,1975).

Grade	Approximate Range Average Fiber Length, In.	Typical Values Surface Area (Rigden), Sq Cm per G
C	1 1/4–1 3/4	1,500
S	1/4–3/4	5,500
S 80	1/4–3/4	9,500
P 25	1/4–3/4	8,300
H	1/8–1/2	7,500
H 80	1/8–1/2	10,000
713	1/8–1/2	13,000
WDS	1/8–3/8	9,000

Table A6: Classification of crocidolit asbestos fibre (Winson,1975)

A8 Uses of Asbestos (Winson,1975).

The uses (Badollet, 1948) of asbestos fibers of all varieties are numerous and only some of the major ones are listed, along with a brief discussion of the products involved.

Crudes No. 1 and No. 2—Chrysotile crudes are usually processed by the customer to produce a long spinning fiber for use in textiles. A desirable fiber for textiles is one that has good flexibility, is soft, low in soluble salts and magnetite, and easily carded without an excess drop in shorts. It should also be free from wood and blasting wire or fuse wire. Fiber of this quality would be desirable for all textile uses, including those for the electrical industry. In some cases, this grade of fiber is used as felts in laminates along with resins to form a strong molded sheet for use in airplanes, boats, etc.

Crocidolite crudes must be carefully processed to produce long fibers which can be used in textiles, gaskets, ropes, or in laminates with resins.

Amosite crudes, after reprocessing, will give a long bulky fiber that is used in blanket insulation or in products requiring a low density and good insulation value. Spinning of amosite can be accomplished, but is difficult.

Group 3 Milled Fibers—Chrysotile fibers that meet this classification are generally used in textiles. Some are used in long fiber asbestos papers, packings, gaskets, brake linings, clutch facings, electrolytic diaphragms, pipe coverings, and insulating blocks. Some of the fibers of this group are now being used in laminates with resins.

Crocidolite may be used for most of the purposes listed previously, providing color is not an objection. It should generally be carefully prepared in a well-opened condition.

Group 4 Milled Fibers—Many grades of fibers in this classification are used in asbestos-cement processes to produce pipe, jackets, boards, sheets, and a variety of hand-molded articles. Other uses are for papers, pipe coverings, packings, gaskets, millboards, and plastics.

Crocidolite, similar to Group 4 chrysotile, is used in asbestos-cement pipes, in some packings and in some gaskets.

Amosite is used in magnesia blocks, pipe coverings, and other insulation compositions when a light density is desired. It is also used in acetylene cylinders to give strength to the calcium silicate mix during curing.

Group 5 Milled Fibers—Fibers of this group sometimes are used as replacements for Group 4 fibers, and therefore the products made with these fibers would include asbestos-cement sheets, corrugated or flat boards, pipe, electrical panels, papers, millboards, pipe coverings, gaskets, packings, brake linings, and plastics.

Crocidolites of this classification are used in asbestos-cement pipes.

Amosites, similar to Group 5 chrysotile although short in length, are finding use in insulating block of light density, such as Thermobestos or similar products, also in lightweight construction materials such as marinite board.

Group 6 Milled Fibers—Chrysotile fibers of Group 6 are used in asbestos-cement shingles, flat sheets, corrugated sheets, boards, brake lining, papers, millboards, putties, and plastics.

Crocidolite of this grading would be considered as too short in length for use in asbestos-cement products and, therefore, it would be classed as a filler and used wherever its physical properties could be employed to advantage.

Amosite of this classification is considered quite short for most purposes, and would probably be used as a cheap filler to free up asbestos-cement slurries prior to pressing.

Group 7 Milled Fibers—These fibers find usage in certain papers, cements, asphalt roof coatings, putties, paints, welding rods, floor tile, and plastics.

Crocidolite and amosite fibers of a length equivalent to Group 7 chrysotile are not known to be used in commercial products unless as a cheap filler where color is not objectionable.

Floats—Chrysotile floats (Badollet, 1952, 1956) are used extensively in plastics, putties, paints, welding rods, and cements.

The selection of asbestos fiber for a particular application will depend upon the processing method, as well as the desired properties of the end product. The following examples outline some of the major uses for asbestos fiber and illustrate pertinent factors which influence the choice of fiber grade and type.

Asbestos Cement Products—Pressure pipe which must conform to hydrostatic test specifications is produced from high quality Group 4 fiber, usually a blend of chrysotile and crocidolite, to ensure a good modulus of rupture. On the other hand, the flexural and impact strength requirements for asbestos cement sheets can usually be met by using a Group 6 fiber. Formulations for corrugated sheets generally include some Group 5 material to improve adhesion of the wet sheets during the forming process.

In all asbestos cement products made by the wet machine process, drainage is an important fiber characteristic since it has direct bearing on the production rate. For this reason, preference may be given to fast filtering fibers and amosite may be included in the formulation as a filter aid.

The requirements for shingles made by a dry process are not so exacting from either the strength or drainage point of view and can be satisfied with a lower quality 6 or 6–7 blend.

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Asbestos Paper—Traditionally asbestos fiber in conjunction with an organic binder has been used for the manufacture of paper and millboard which, in turn, were converted to roofing felt, pipe coverings, electrical insulations, and many other products. Various blends of Groups 4, 5, and 6 fibers are used for this application, depending upon the desired strength and porosity of the paper.

More recently, a latex-asbestos process has been developed in which a long clean Group 7 fiber having a high surface area is coated with latex rubber by a chemical precipitation method and the resulting furnish formed into a continuous sheet on a paper machine. A large proportion of this latex asbestos paper is used as an underlayment for vinyl-rolled floor covering. A lesser amount is used in the manufacture of gaskets.

Friction Materials—This product line cannot be related to any particular fiber group, since it spans the complete spectrum from Group 3 spinning grades to the shorter Group 7.

The explanation lies in the wide variety of products, which fall within the general classification of "friction materials," and the equally diversified manufacturing processes involved.

Clutch plates are made from an asbestos open-weave cloth impregnated with resin and bonded to a steel disk. A similar product can be manufactured by molding a dry resin-fiber blend under conditions of high temperature and pressure onto a packing plate. For the first method, a Group 3 fiber is required, whereas the molding process utilizes a Group 5.

Automobile brake linings bonded to a steel shoe are usually made from Group 7 fiber in a semi-wet extrusion process while heavy blocks for railcars and large vehicles use Group 5 or 6 fiber dry-molded and machined to finished dimensions.

Group 5 fiber is also used extensively in disk brake pad formulations.

Sheet Packing—Latex asbestos paper made from Group 7 fiber can be densified and used for gasketing, but most sheet packing material is formed on a sheeter machine by a calendering process. This latter method requires a longer fiber in the Group 4 to 5 range, which has been cleaned and opened. The fiber is blended with natural or synthetic rubber, plasticizers, and other ingredients in a high shear mixer to form a dough which is later calendered into sheets of various thicknesses.

Floor Tile—A large volume of Group 7 fiber is supplied to manufacturers of vinyl floor tile. This product requires a short, clean, well opened Group 7 fiber having a high degree of uniformity in such properties as length distribution, absorption, and color. This latter feature is particularly important to the industry because of the need for matching of shades from different production runs.

Asphalt Products—Group 7 asbestos fiber in combination with asphalt and various solvents form the basis of a wide variety of products often classified under the catchall heading of "Blackline."

These include spray or brush-on roof coatings, sound deadeners for automobile body panels, and caulking components.

In recent years, automobile underbody protective coatings applied by airless spray equipment have provided an outlet for Group 7 fiber. Since the finished compound must pass through an orifice 0.021 to 0.028 in. in diameter under high pressure during application to the automobile, the fiber used must meet strongest specifications on fineness and viscosity building properties.

Short Group 7 chrysotile asbestos added to hot asphalt paving mix helps to improve characteristics of toughness, flexibility, and water impermeability. Asbestos modified pavements have proved successful in high traffic density areas, such as busy street intersections, bus stops, and bridge decks.

Caulking Compounds—Combinations of long asbestos with cement and other ingredients, along with waterproofing resins, are used to produce special types of caulking compounds.

In many cases, short asbestos and floats are also combined with various types of resins and other materials to produce a soft plastic caulking compound that remains soft or it may be controlled so as to set up as a hard mass.

Plastics—Structural materials using plastics reinforced by asbestos or as a combination of asbestos and glass are now of considerable importance commercially. The asbestos may be in the form of a mat, or as paper or cloth to form laminates with resins such as polyesters, phenolics, thermosetting silicones, melamines, and furanes.

The use of long fiber chrysotile, crocidolite, and in some cases amosite, in the form of felts or papers and impregnated with resins produces a tough product of high strength and good heat resistance. These products have been used in aeroplane wings in England and in small sailing boats, radar scanner aerials, aircraft tanks, automobile bodies, and other products including rocket tubes, missile nose cones, and other parts.

In some cases, asbestos in the form of cloth or a millboard type is impregnated by resins to obtain a strong sheet for structural use.

Short Group 7 fiber and floats are also used extensively as a fibrous filler for the production of molded phenolic resin and polyester parts, such as automobile heater and air conditioner housings, electric kettle basis, and other appliance parts. In such applications, freedom from abrasive particles is especially important to hold die wear at minimum level.

Joint Filler—Another interesting use for short Group 7 fiber and floats is in the manufacture of joint filler cements and texture paints. Here again, fineness and whiteness are critical properties of the fiber. Also, since the viscosity of the mix after the addition of a prescribed amount of water must be consistent from batch to batch, the absorptive capacity of the asbestos must be controlled within very narrow limits.

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