Chapter 6

The GEOLOGIC OCCURRENCES and HEALTH HAZARDS of AMPHIBOLE and SERPENTINE ASBESTOS

Malcolm Ross

INTRODUCTION

The problem

The widespread use of amphibole and serpentine asbestos[1] by industrial society has contributed greatly to human safety and convenience by service in brake and clutch facings, electrical and heat insulation, fire-proofing materials, cement water pipe, tiles, filters, packings, construction materials, and many other products. Yet, while these very tangible benefits were accruing to our society, some asbestos workers were dying of asbestosis, lung cancer, and mesothelioma.

The hazards of certain forms of asbestos under certain conditions have been so great that several countries have taken extraordinary actions to greatly reduce or even ban their use. Recent experiments with animals demonstrate that the commercial asbestos minerals as well as other fibrous materials can cause tumors to form when the fibrous particles are implanted within the pleura.[2] These experiments have convinced some health specialists that asbestos-related diseases can be caused by many types of elongate particles; the mineral type, according to these health specialists, is not the important factor in the etiology of

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[1]At present, the most widely used definition of asbestos by various groups concerned with environmental health problems is from the notice of proposed rule-making for "Occupational Exposure to Asbestos" published in the *Federal Register* (Oct. 9, 1975, p. 47652, 47660) by the U.S. Occupational Safety and Health Administration (OSHA). In this notice, the naturally occurring amphibole minerals amosite, crocidolite, anthophyllite, tremolite, and actinolite and the serpentine mineral chrysotile are classified as asbestos if the individual crystallites or crystal fragments have the following dimensions: length greater than 5 micrometers, maximum diameter less than 5 micrometers, and a length to diameter ratio of 3 or greater. Any product containing *any* of these minerals in this size range is also defined as asbestos.

[2]The lungs are invested by a double membrane, the two layers of which form the closed pleural sac. For discussion of these animal experiments see Stanton and Layard (1978) and Pott (1978).

disease, but rather the size and shape of the particles which enter the human body.

The question now before the United States health and regulatory establishment is whether the hazards of asbestos outweigh the benefits. Should the asbestos minerals and perhaps other asbestos-like minerals be banned from use? Minerals belonging to the amphibole group are particularly important in this regard, for they are ubiquitous and commonly have crystalline habits which are considered by some to be asbestos-like.

The dilemma

The concern for human health, the great usefulness of many asbestos products, the appearance of asbestos minerals or asbestos-like minerals in the natural background and in many kinds of mining operations, and the uncertainty of the exact health effects of different kinds of minerals, different mineral particle sizes, and different mineral dust concentrations combine to present a formidable problem to minerals scientists, the minerals industries, and legal and health professionals. Must the use of all commercial asbestos be stopped? Must all mine dusts containing such particles be controlled to the lowest feasible levels and wastes from those mines be considered toxic and thus isolated from surrounding air and water?

To obtain an insight so that we might intelligently address these questions, I will review the role of asbestos in the world economy, past and present, the important geological occurrences of commercial amphibole and chrysotile asbestos, and the health hazards of asbestos use. As we will see, the six asbestos minerals utilized in commerce are not identical in crystal structure, chemical composition, abundance, and geologic occurrence; nor do the different asbestos dusts have the same impact on human health. Evidence will be presented to indicate that many of the benefits obtainable from asbestos may be retained with minimal health risk through utilization of the common chrysotile form of asbestos, provided that dust emissions are controlled to levels presently in force at the mines and mills of Quebec. It would appear that, instead of treating all asbestos minerals and other fibrous industrial and gangue minerals as equally potent carcinogens, each mineral should be examined on its own merits with regard to its usefulness to society and its potential to cause disease.

Standard references published over the past 50 years usually list six forms of asbestos; the amphibole varieties are amosite, crocidolite, anthophyllite, tremolite, and actinolite, and the serpentine variety is chrysotile. A detailed understanding of the chemistry and crystal structures of these asbestos minerals postdates their discoveries; thus, some of the older literature can be confusing with regard to mineral identifications.

The commercial deposits of asbestos contain one of the following minerals: chrysotile, $Mg_3Si_2O_5(OH)_4$; amosite, $(Fe^{2+},Mg)_7Si_8O_{22}(OH)_2$ (a variety of grunerite); crocidolite, $Na_2(Fe^{2+},Mg)_3Fe^{3+}_2Si_8O_{22}(OH)_2$ (a variety of riebeckite); "fibrous" anthophyllite, $(Mg,Fe)_7Si_8O_{22}(OH_2)$; and "fibrous" tremolite and actinolite, $Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$. Tremolite and actinolite are now, as they were in the past, of little economic importance; anthophyllite is of little economic importance now. About 95 percent of the commercial asbestos now used in the United States is chrysotile, of which about 90 percent is imported from Canada.

Amphibole asbestos

The crystal structures of the amphibole asbestos minerals are composed of strips or ribbons of linked polyhedra, which join together to form the three-dimensional crystal. The individual strips are composed of three elements -- two double chains of linked $(Si,Al)O_4$ tetrahedra that form a "sandwich" with a strip of linked MgO_6, FeO_6, or AlO_6 octahedra. The structural relationship of the upper double tetrahedral chain to the octahedral part of the strip is shown in Figure 1. The three-dimensional arrangements of these strips or "I-beams" in orthoamphibole (anthophyllite) and in clinoamphibole (tremolite, amosite, actinolite, and crocidolite) are shown in Figure 2. Complete reviews of the amphibole crystal structures are given by Cameron and Papike (1979) and Hawthorne, Chapter 1, this volume.

Amosite is the very rare asbestiform variety of grunerite, $(Fe,Mg)_7Si_8O_{22}(OH)_2$; the name is derived from the word *Amosa* -- an acronym for the company "Asbestos Mines of South Africa" (Hall, 1918, p. 13-14). This valuable commercial asbestos, mined only in the Transvaal Province of South Africa, was first discovered in 1907 in

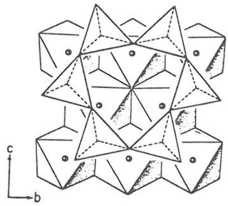

Figure 1. Structural relationship between the upper double chain of linked (Si,Al)O_4 tetrahedra and the octahedral part of the amphibole strip or "I-beam." The circles represent Mg, Fe, or Al atoms in octahedral coordination; at the apices of the polyhedra are oxygen atoms. Tetrahedral Si and Al atoms are not shown. The "I-beams" extend infinitely in a direction parallel to the *c*-axis (the fiber axis). The width of the "I-beam" in the *b*-direction is three octahedra. Modified from Papike and Ross (1970).

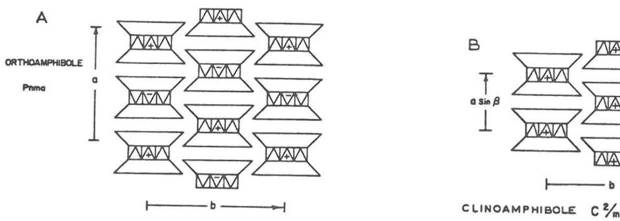

Figure 2. Arrangement of the amphibole strips or "I-beams" in (A) orthoamphibole (space group *Pnma*) and (B) clinoamphibole (space group *C*2/*m*). The "I-beams" are viewed end-on (parallel to the fiber *c*-axis). The central portion of the "I-beam" is composed of (Mg,Fe,Al)O_6 octahedra; the upper and lower portions are composed of double chains of (Si,Al)O_4 tetrahedra. The I-beams are stacked in two ways: (1) +++... (clinoamphibole), and (2) ++--... (orthoamphibole). Modified from Papike and Ross (1970).

Table 1. Chemical analyses and formulas of amphibole asbestos.

	Amosite		Crocidolite					Anthophyllite
	1.	2.	3.	4.	5.	6.	7.	8.
SiO_2	49.70	51.30	50.90	50.70	52.00	55.65	52.85	57.20
Al_2O_3	0.40	nil	nil	0.70	nil	4.00	0.18	--
Fe_2O_3	0.03	0.90	16.85	18.30	16.05	13.01	18.55	0.13
FeO	39.70	35.50	20.50	17.50	17.65	3.84	14.94	10.12
MnO	0.22	1.76	0.05	0.06	trace	trace	trace	--
MgO	6.44	6.90	1.06	3.05	4.28	13.09	4.64	29.21
CaO	1.04	0.95	1.45	1.30	1.20	1.45	1.07	1.02
K_2O	0.63	0.51	0.20	trace	0.06	0.39	0.05	--
Na_2O	0.09	0.05	6.20	5.30	6.21	6.91	5.97	--
H_2O^+	1.83	2.31	2.37	2.53	2.43	1.78	2.77	2.18
H_2O^-	0.09	0.05	0.22	0.29	0.26	trace	0.22	0.28
CO_2	0.09	0.25	0.20	0.45	0.09	trace	0.23	--
	100.26	100.48	100.00	100.18	100.23	100.12	101.47	100.14
NUMBER OF IONS ON BASIS OF O=22, OH=2								
Si	7.898	8.055	7.949	7.823	7.942	7.791	7.927	7.848
Al	0.075	--	--	0.127	--	0.209	0.032	--
	7.973	8.055	7.949	7.950	7.942	8.000	7.959	7.848
Al	--	--	--	--	--	0.451	--	--
Fe^{3+}	0.004	0.106	1.980	2.125	1.844	1.371	2.094	0.013
Fe^{2+}	5.277	4.662	2.678	2.259	2.254	0.450	1.874	1.161
Mn	0.030	0.234	0.007	0.008	--	--	--	--
Mg	1.525	1.615	0.247	0.701	0.974	2.731	1.037	5.972
Ca	0.177	0.160	0.243	0.215	0.196	0.218	0.172	0.150
K	0.128	0.102	0.040	--	0.012	0.070	0.010	--
Na	0.028	0.015	1.877	1.585	1.839	1.875	1.736	--
	7.165	6.894	7.072	6.893	7.119	7.166	6.923	7.296

1. Amosite, Penge, Transvaal, South Africa (Hodgson, 1979)
2. Amosite, Weltevreden, Transvaal, South Africa (Hodgson, 1979)
3. Crocidolite, Koegs, Cape Province, South Africa (Hodgson, 1979)
4. Crocidolite, Kuruman, Cape Province, South Africa (Hodgson, 1979)
5. Crocidolite, Pomfret, Cape Province, South Africa (Hodgson, 1979)
6. Crocidolite, Cochabamba, Bolivia (Hodgson, 1979)
7. Crocidolite, Hammersley Range, W. Australia (Hodgson, 1979; see also Trendall and Blockley, 1970)
8. Anthophyllite, Paakkila, Finland (Hodgson, 1979, see also Haapala, 1936)

Sekukuniland. Until relatively recently, its true relationship to grunerite was not known. It is now clear (Hutchison *et al.*, 1975; Champness *et al.*, 1976) that amosite and grunerite are the same mineral species, having identical crystal structures and similar chemical compositions. The chemical compositions of samples of amosite from the important Penge and Weltevreden mining areas are given in Table 1.

Crocidolite is the asbestiform variety of riebeckite, ideally $Na_2(Fe^{2+},Mg)_3Fe^{3+}_2Si_8O_{22}(OH)_2$, and has been mined in only four localities: in the Transvaal and Cape Provinces of South Africa, in the Hammersley Range area of Western Australia, and in the Cochabamba area of Bolivia. Only the South African mines are still active. Five chemical analyses of crocidolite from three of these areas are given in Table 1.

The only other form of amphibole asbestos that has been mined commercially on a significant scale is anthophyllite, $(Mg,Fe)_7Si_8O_{22}(OH)_2$, from the Paakkila area of East Finland, a chemical analysis of which is given in Table 1.

There are numerous reports of minor occurrences of tremolite asbestos, $Ca_2Mg_5Si_8O_{22}(OH)_2$, and relatively few reports of actinolite asbestos, $Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$, occurrences. No mining of these asbestos minerals on a significant scale has occurred, save perhaps some of the early mining of tremolite asbestos in the Alps of northern Italy. Much of the reported "tremolite asbestos" from this area may have actually been chrysotile. Asbestiform hornblende has been reported (for example, Shannon, 1926, p. 56-57; Hall, 1918, p. 97) but has not apparently been used in commerce.

Chrysotile asbestos

Chrysotile, one of the three common polymorphs of serpentine (lizardite, antigorite, and chrysotile), is generally fibrous, although non-fibrous massive varieties are known. The structure of chrysotile asbestos consists of double sheets, each double sheet being composed of a layer of linked SiO_4 tetrahedra that is coordinated to a second layer of linked $MgO_2(OH)_4$ octahedra through the sharing of oxygen atoms. This composite double sheet, due to a misfit between the SiO_4 and $MgO_2(OH)_4$ layers, rolls up like a window shade to form long hollow tubes. The diameters of the individual tubes are approximately 25 nm; the lengths vary from a few hundred to a few million nanometers. Chemical analyses of chrysotile asbestos from four important mining localities are given in Table 2.

ASBESTOS IN THE WORLD ECONOMY

Early beginnings

While the general use of asbestos in international commerce dates only to the late 19th century, its utility in human culture goes back to at least 2500 B.C. Archeological studies (Europaeus-Äyräpää, 1930) show that the inhabitants of the Lake Juojärvi region of East Finland knew how to strengthen earthenware pots and cooking utensils with anthophyllite asbestos. This asbestos probably came from the same areas where it was commercially exploited in recent times. According to Huuskonen (1980; see also Europaeus Äyräpää, 1930; Noro, 1968), the use of asbestos-strengthened ceramic wares began during the Stone Age and continued throughout the Bronze Age and into the Iron Age. The use of such utensils spread over a wide area of Finland, Scandinavia, and Russia. The most important modern use of asbestos, to strengthen materials, was apparently also the first use -- dating back several thousand years.

Until recently, however, most other uses of asbestos were trivial; its fabrication into such curiosities as cremation cloth (Pliny refers to this as a rare and costly cloth -- linum vivum -- the funeral dress of kings), tablecloths (reputedly, Charlemagne, or according to some writers, Charles V, astonished guests by throwing the cloth into fire and later withdrawing it cleansed, but unconsumed), and lamp wicks (Plutarch recorded that the vestal virgins used "perpetual" lamps). The fabrication of lamp wicks may have been a cottage industry during certain times in history; Herodotus clearly documented use of such asbestos wicks in the earlier Greek civilization. Even well into the last century, asbestos could not be regarded as a product of commerce unless one includes such endeavors as the small industry developed in Russia during the rule of Peter the Great, where chrysotile asbestos from the Urals was used for a short period in the production of textiles.

In the 1860's and 1870's the market for asbestos products rapidly

Table 2: Chemical analyses and formulas of commercial chrysotile asbestos (Hodgson, 1979)

	1.	2.	3.	4.
SiO_2	38.75	39.00	39.70	39.93
Al_2O_3	3.09	4.66	3.17	3.92
Fe_2O_3	1.59	0.54	0.27	0.10
FeO	2.03	1.53	0.70	0.45
MnO	0.08	0.11	0.26	0.05
MgO	39.78	38.22	40.30	40.25
CaO	0.89	2.03	1.08	1.02
K_2O	0.18	0.07	0.05	0.09
Na_2O	0.10	0.07	0.04	0.09
H_2O^+	12.22	11.37	12.17	12.36
H_2O^-	0.60	0.77	0.64	0.92
CO_2	0.48	1.83	2.13	1.04
	99.79	100.20	100.51	100.22

NUMBER OF IONS ON BASIS OF O=5, OH=4

	1.		2.		3.		4.	
Si	1.845	2.000	1.851	2.000	1.885	2.000	1.882	2.000
Al	0.155		0.149		0.115		0.118	
Al	0.018	3.047	0.112	3.013	0.062	3.025	0.100	3.016
Fe^{3+}	0.057		0.019		0.010		0.004	
Fe^{2+}	0.081		0.061		0.028		0.018	
Mn	0.003		0.004		0.010		0.002	
Mg	2.823		2.704		2.853		2.827	
Ca	0.045		0.103		0.055		0.052	
K	0.011		0.004		0.003		0.005	
Na	0.009		0.006		0.004		0.008	

1. Chrysotile, King Beaver Mine, Thetford Mines, Quebec
2. Chrysotile, Asbest, Urals, U.S.S.R.
3. Chrysotile, Shabani Mines, Zimbabwe
4. Chrysotile, Havelock Mine, Swaziland

Table 3. World asbestos production in 1978 (Clifton, 1979)

Fiber Locality	Production (in thousands of metric tonnes)
Chrysotile	
North America	
Canada	1620
United States	93
South America	
Argentina	1
Brazil	100
Europe	
Bulgaria	21
Italy	162
U.S.S.R.	2582
Yugoslavia	10
Africa	
Zimbabwe	210
South Africa	118
Swaziland	48
other	1
Asia	
China	210
Cyprus	37
India	21
Japan	7
Korea	7
Taiwan	1
Turkey	10
Oceania	
Australia	58
(World chrysotile total)	5317
Crocidolite	
South Africa	210
Amosite	
South Africa	71

changed, probably for three reasons: the need for insulation for the new steam technology, the formation of an international trading company of Italian and English entrepreneurs, and the reopening of the chrysotile asbestos deposits of northern Italy and simultaneous exploitation of the vast chrysotile resources in Quebec. The supply for the first time was ample, and the market was ready.

The modern industry

The reopening of the asbestos deposits of northern Italy, deposits which had previously been worked as far back as Roman times, serves to mark the beginning of the modern asbestos industry. The Italian asbestos was unusually silky and long fibered[3] and thus readily woven into textiles. The shrouds and cloths of antiquity may have been made from this asbestos.

By 1890 the modern asbestos industry was full blown, with hundreds of applications being introduced (Jones, 1890); by the turn of the century the large South African crocidolite deposits had been opened up, and the Russian deposits in the Urals were once again producing in large quantity. Within a few years, the amosite deposits of the Transvaal would be exploited.

From the time of the first recorded use of asbestos by Stone Age man to 1900, the total world production of all types of fiber was probably about 200,000 metric tonnes, certainly no more than 300,000 tonnes. Of this, 150,000 tonnes came from Quebec. By 1980 over 100 million tonnes of asbestos had been mined throughout the world; of this over 90 percent was chrysotile and over 5 percent crocidolite and amosite. Total production of anthophyllite asbestos to date is probably no more than 400,000 tonnes, 350,000 tonnes being produced by Finland alone. Production of tremolite asbestos has been sporadic; it was mined in various parts of the world for short periods of time. Total production to date for this

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[3]Two samples of Italian asbestos on deposit at the U.S. National Museum are both chrysotile. One, U.S.N.M. No. 73539, is from "Piedmonte," Italy, and was acquired by the museum in 1900 from the Isaac Lea Collection. The fibers in this sample are up to 120 cm long! The second sample, U.S.N.M. No. R3172 (Roebling Collection) is from Val Malenco, Sondrio, Lombardia, Italy. Fibers are up to 15 cm long in this specimen.

form of asbestos is probably no more than a few thousand tonnes. Commercial exploitation of actinolite asbestos is practically unknown.

The world asbestos production for 1978 is given in Table 3. Russia leads with 46.1 percent and Canada is second with 28.9 percent of the world output. Both countries mine only chrysotile asbestos, and most of the fiber comes from the Urals and Quebec. The third leading asbestos producer is the Republic of South Africa (7.1 percent); the asbestos ore consists of amosite, crocidolite, and chrysotile. These three countries furnished 82.1 percent of the world's asbestos in 1978. The other countries listed in Table 3 produce mostly chrysotile.

Modern asbestos uses

As alluded to before, heat insulation was one of the most important uses of asbestos during the early beginnings of the modern industry; apparently the first application for this purpose was in 1866 (Bowles, 1937, p. 9). The principal uses of asbestos in the United States in 1978 in order of importance were as follows: in cement pipe (145,800 metric tonnes), in flooring products (122,400), in friction materials (81,600), in roofing products (58,300), in asbestos cement sheet (29,200), in coatings and compounds (29,100), in paper (29,100), in packings and gaskets (23,300), and in insulation (14,300) (Clifton, 1979).

MAJOR GEOLOGICAL OCCURRENCES OF AMPHIBOLE ASBESTOS

There are many minerals, including the amphiboles and chrysotile, that are described variously as fibrous, asbestiform, acicular, filiform, and prismatic, terms which suggest an elongate habit. Although such minerals are extremely common, in only relatively few places do they obtain suitable physical and chemical properties to be valuable as commercial asbestos. Locally, amphibole minerals may show an asbestiform habit, for example in vein fillings and in areas of secondary alteration, but usually they do not appear in sufficient quantity to be profitably exploited.

Deposits of commercial asbestos are found in four types of rocks: (1) banded ironstones (amosite and crocidolite), (2) alpine-type ultramafic rocks, including ophiolites (anthophyllite, tremolite, and chrysotile), (3) stratiform ultramafic intrusions (tremolite and chrysotile), and (4) serpentinized limestone (chrysotile). Of these, the banded ironstones of South Africa and Western Australia and the alpine-type ultramafic rocks of East Finland are or were the only major sources of amphibole asbestos.

Amosite and crocidolite in ironstones of South Africa

The mining of amphibole asbestos is now essentially confined to South Africa.[4] The amosite and crocidolite asbestos occur in the banded ironstones of the Transvaal Supergroup, a thick succession of Precambrian sediments (∿ 2200 m.y., Truswell, 1977, p. 42) with widespread outcrops in the Transvaal and Cape Provinces and in southeastern Botswana. The two asbestos producing localities are the *Transvaal Asbestos Field* in the north-central part of the Transvaal Province and the *Cape Asbestos Field* in the northern Cape. At present about 200,000 tonnes of amphibole asbestos are produced yearly from these two fields.

Transvaal Asbestos Field. This field stretches from Chuniespoort easterly to beyond Penge, Transvaal Province, a distance of about 100 km (Fig. 3). Most of the amosite presently mined is derived from the Penge area, about 80 km north of Lydenburg. Minor amounts of amosite and crocidolite are mined intermittently in the Chuniespoort-Malips Drift area to the west of Penge (Dreyer and Robinson, 1978). The Penge area is sometimes referred to as the "Lydenburg asbestos field" and the Chuniespoort-Malips Drift area as the "Pietersburg asbestos field."

In the Transvaal the rock members of the Transvaal Supergroup consist essentially of quartzite, shale, dolomite, and conglomerate at the base (Wolkberg Formation, Black Reef Series), dolomite, banded ironstone, and shale in the center zone (Dolomite Series); and quartzite, shale and hornfelses at the top (Pretoria Series). The asbestos-bearing rocks lie within the Banded Ironstone Stage of the Dolomite Series (Fig. 3). These rocks have been intensely folded along two major fold axes (Dreyer and Robinson, 1978), the folding predating the deposition of the Pretoria Series. The banding within the ironstones is fine and regular; the

[4]Small amounts of anthophyllite and tremolite asbestos come into the international market sporadically, at most a few thousand tonnes a year. These types of fiber are generally from small, marginally profitable, deposits.

Figure 3. Index map of the crocidolite and amosite asbestos-bearing iron formations of the Transvaal and Cape Provinces of South Africa. After Truswell (1977).

light colored bands consist of chert with some siderite, the dark bands of magnetite and grunerite. Within the banded ironstone sequences the asbestos-bearing seams occupy definite stratigraphic horizons, generally known as the Lower Zone, the Main Zone, the Short Fibre Zone, and the Upper Zone. Some intermediate zones are developed locally. Each zone consists of a large number of individual fiber seams or groups of seams which are given local names (Coetzee *et al.*, 1976). In the Pietersburg asbestos field amosite and crocidolite are sometimes observed occurring in adjacent seams (Hall, 1930, Fig. 38, p. 212). East of the Mohlapitse River, crocidolite decreases rapidly, so that only amosite is found in the Lydenburg asbestos field near Penge.

Within the Transvaal Province there is evidence of thermal metamorphism of the Transvaal Supergroup rocks as a result of the intrusion of the Bushveld Igneous Complex. For example, the shales of the Pretoria Series overlying the banded ironstones were recrystallized to hornfelses, scapolite appears in the dolomites underlying the ironstones, and amphibolization took place throughout most of the banded ironstone sequence. Crystallization of the amphibole asbestos, however, took place after emplacement of the diabasic sills (considered forerunners of the main Bushveld intrusion) and before cooling of the main body of the Complex (Cilliers, 1964).

Cape Asbestos Field. This field is in Griqualand West, Cape Province, 700 km to the west of the asbestos mining areas of the Transvaal. It lies along a line of low hills (Asbestos Mountains, Kuruman Hills) that stretches from 40 km south of Prieska, northward past Kuruman to Pomfret near the Botswana Border, a distance of 480 km (Fig. 3). The crocidolite asbestos-bearing ironstones of this area are included within the Pretoria Series of the Transvaal Supergroup and are suggested to be correlated with the Pretoria Series rocks to the east in the Transvaal (Cilliers, 1964, p. 581). Stratigraphic correlations between the Transvaal and Cape regions are subject to somewhat different interpretation (Cilliers, 1964; Cilliers and Genis, 1964; Beukes, 1973, 1980). New nomenclature proposals by Beukes (1980) place the crocidolite-bearing banded ironstones of the Cape within the Griquatown and Kuruman Iron Formations of the Asbesheuwels Subgroup. Cilliers (1964, p. 5881) states that it may be accepted that the banded ironstones in the Cape Province and in the Transvaal were formed contemporaneously and under similar conditions. The asbestos deposits of the Cape are generally located in the monoclinal folds. Metamorphism is generally absent.

Formation of banded ironstones. The origin of the Precambrian banded ironstones of South Africa is still the subject of much debate, but it is possible to summarize some of the main ideas on their paragenesis. The deposition of the sediments probably occurred in relatively shallow water, in some places in saline basins. Iron and silica were derived from normal weathering processes. Primary precipitates such as silica and hydrous iron oxides and silicates may have been the precursors to the later-formed stilpnomelane , minnesotaite, and riebeckite. Biochemical actions of organic matter also probably had an important influence on the mineral chemistry. The change of amphibole mineralogy from amosite in the Penge area, mixed amosite-crocidolite in the Chuniespoort-Malips Drift area, to crocidolite in the Cape suggests that there was a gradual change of conditions of sediment formation: deposition in a predominantly fresh water environment in the Transvaal to a predominantly saline environment in the Cape (Cilliers, 1964).

The reason why the amphiboles crystallized in an asbestiform habit rather than the typical prismatic form is a subject of some interest. It is pertinent to note the comments of Dreyer and Robinson (1978), who state (p. 3-4) "the greatest development of fibre occurs where two sets of folds intersect to form domes or basins. It is firmly believed that the development of fibre deposits could only have taken place in a favourable stress environment." For further comments on crystal growth of asbestos minerals in stress fields, see Zoltai (Chapter 5, this volume).

Crocidolite in ironstones of Western Australia

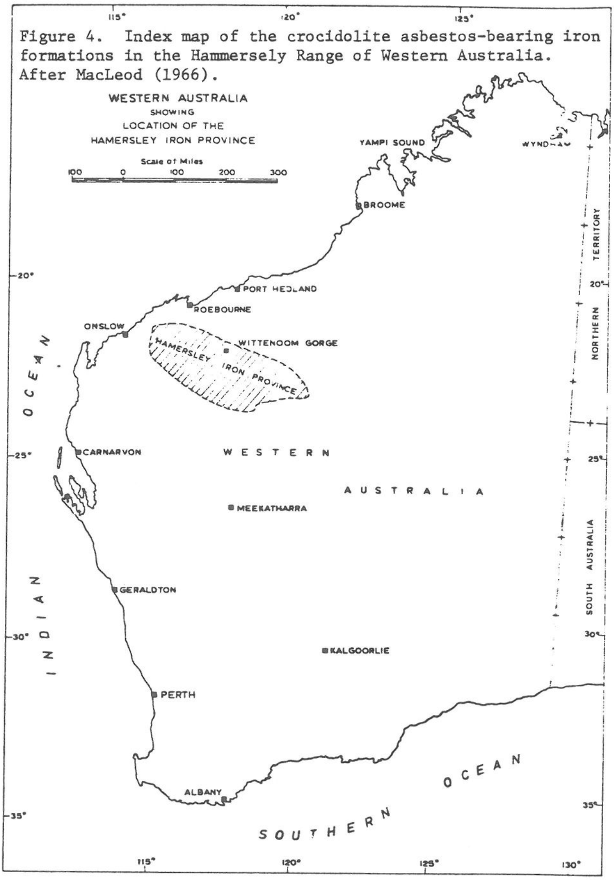
Crocidolite asbestos is also found in the banded ironstones of the Hamersley Iron Province, Western Australia (Fig. 4). These formations are remarkably similar to those of the Cape Province of South Africa and are included among the great iron formations of the world which formed under very similar conditions and during a single geologic epoch approximately 1900 to 2500 m.y. ago (James and Sims, 1973).

The banded ironstones are widely distributed in the Marra Mamba, Brockman, and Boolgeeda Iron Formations of the Hamersley Group, Mount Bruce Supergroup. The ironstones are approximately 2000 m.y. old (Trendall, 1973). Although riebeckite is widely distributed in these three iron formations, it is only abundant in fibrous form (crocidolite) in four narrow zones.

The Hamersley ironstones are thought to have formed in much the same way as those of South Africa, by precipitation of volcanically derived iron and silica in a shallow basin. Massive riebeckite developed during diagenesis from previously existing minerals, with crocidolite asbestos crystallizing later in a stress environment. The major asbestos deposits are confined to the northern limb of the broad syncline of the Hamersley Range (Trendall and Blockley, 1970). These authors propose a "stress-reversal" for asbestos growth; they state (p. 18) "Crocidolite grew later by splitting and dialation of magnetite mesobands in banded iron formation as a relief from balanced compression from two sides in particular structural situations, where gravitational sliding opposed 'tectonic' stress."

Crocidolite mining in Western Australia began on a very small scale in 1933, but it was not until 1944 that significant production started. By 1966, the year of the final closing of the mines, 138,000 tonnes of crocidolite had been shipped. Ninety-eight percent of this fiber came from two mines in the Wittenoom Gorge (Fig. 4), the Colonial Mine and the Wittenoom Mine. Here mining was entirely within the Dales Gorge Member of the Brockman Iron Formation (Trendall and Blockley, 1970).

Figure 4. Index map of the crocidolite asbestos-bearing iron formations in the Hammersely Range of Western Australia. After MacLeod (1966).



Anthophyllite in Alpine-type ultramafic rocks of East Finland

In the Karelian Mountains of East Finland there occur a number of ultramafic bodies in the form of pods or lenses which were originally dunite or enstatite-bearing peridotites. These alpine-type serpentinized ultramafic masses are thought to have been once a part of much larger slabs of oceanic or continental mantle material, which during the mountain building episode broke up into smaller volumes of rock and were injected upwards into overlying rocks of the Karelidic schist belt. The Karelide metasediments are thought to range in age from ∿2200 to ∿2000 m.y. (Simonen, 1980). Late Karelian granites (∿1900 m.y.) were injected into the schist belt rocks, and where they make contact with the serpentinized periotites, commercial quality anthophyllite asbestos is developed -- at Paakkila, located on the northern shore of Lake Juojärvi, East Savo, and at Maljasalmi, 10 km to the southeast.

The main asbestos producing area at Paakkila is comprised of biotite gneiss with numerous pods or lenses of ultramafic rock cut by Maarianvaava granite (Fig. 5). These pods typically contain relict olivine surrounded by serpentine aggregates and bundles of anthophyllite needles. Commonly the anthophyllite needles penetrate poikiloblastically the relict olivine (Wiik, 1953). Talc sometimes has replaced anthophyllite and olivine; there is not much serpentinization (Haapala, 1936).

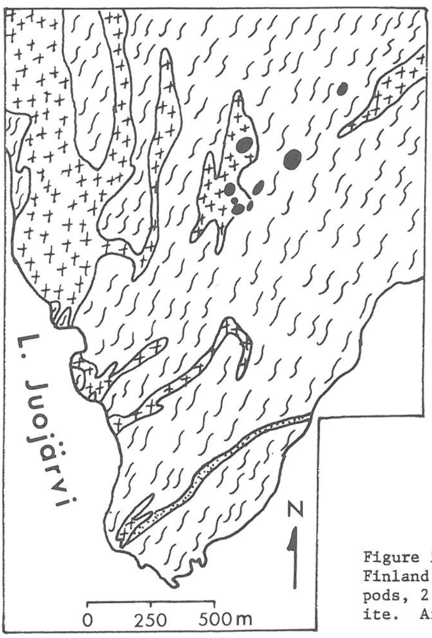


Figure 5. Geological map of Paakkila region, East Finland. 1 - anthophyllite-bearing ultramafic pods, 2 - granite, 3 - biotite gneiss, 4 - quartzite. After Aurola (1954, p. 96).

The country rocks in the Maljasalmi area, the secondary anthophyllite asbestos producing locality, are Karelian mica schist cut by granite pegmatite dikes. The serpentinized peridotites within the schists are similar to those of Paakkila, with the exception that anthophyllite has clearly replaced enstatite. Relict enstatite is still present, penetrated by needles of anthophyllite; in addition, olivine-bearing serpentine, talc, and chlorite have been observed (Aurola, 1954).

The anthophyllite asbestos deposits at Paakkila were first leased in 1907 but not worked to any degree until 1918, when they were taken over by Suomen Mineraali Oy and operated continuously until production stopped for economic reasons in 1975. Paakkila produced in total 350,000 tonnes of asbestos, of which 230,000 tonnes was exported (Huuskonen *et al.*, 1980). The asbestos mine and mill at Maljasalmi was operated contemporaneously by the same company, but the ore was inferior to that from Paakkila.

MINOR GEOLOGICAL OCCURRENCES OF AMPHIBOLE ASBESTOS

Anthophyllite asbestos

Small deposits of anthophyllite asbestos have been worked in many localities, but none approached the Paakkila output of 350,000 tonnes. In the United States anthophyllite has been mined in a number of localities, particularly in Georgia, North Carolina, Idaho, Maryland, and Massachusetts. Some of the more active mines were the Sall Mountain and Calhoun mines, Sall Mountain, Georgia; the Hollywood mine, Habersham County, Georgia; the Kamiah mine, Idaho County, Idaho; the Bok Asbestos mine and Alberton mine, Baltimore County, Maryland; and the Pelham quarry, Hampshire County, Massachusetts. The mode of occurrence of anthophyllite asbestos in these localities is very similar to that in Paakkila and Maljasalmi, East Finland. Typically these anthophyllite deposits are found in metamorphosed ultramafic bodies, generally serpentinized and amphibolized dunites and harzburgites caught up as inclusions within the country rock schists and gneisses. In localities within the Appalachian Orgenic belt, metamorphism is regional and repeated; in Kamiah, Idaho, much of the metamorphism was accomplished by the intrusion of the Idaho batholith. Granitic intrusions are noted in some localities and may have contributed to the metamorphism, particularly in regard to supply of heat, SiO_2, and H_2O.

The Kamiah deposit (Anderson, 1931) is particularly interesting in its similarity to the Finnish deposits. Here also the ultramafic lenses (dunites and harzburgites) are included within mica schists and gneisses. Anthophyllite clearly replaced olivine and enstatite, for needles grew into the relict grains. In addition, anthophyllite replaces antigorite, the antigorite having previously replaced olivine. Talc is a minor constituent in the Kamiah deposit but replaces anthophyllite, antigorite, and olivine. The various assemblages observed at Kamiah, Paakkila, and Maljasalmi can be explained with the phase diagrams suggested by Hemley *et al.* (1977), three of which are shown in Figure 6.

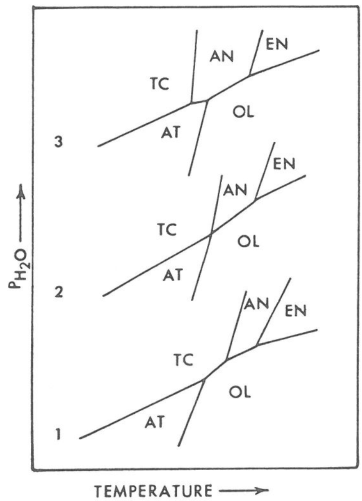


Figure 6. Proposed phase relations in the system $MgO-SiO_2-H_2O$ (Hemley *et al.*, 1977). EN - enstatite, AN - anthophyllite, AT - antigorite (serpentine), OL - olivine, TC - talc. Suggested reactions which could occur at lower or higher P_{H_2O} (1, 2, or 3) are: EN → AN (M,K), OL → AN(P,K), OL → AT (P,K), AT → TC (K), AN → TC (P,K). Reaction at lower P_{H_2O} only: OL → TC (P,K). Reaction at higher P_{H_2O} only: AT → AN (K). M - Maljasalmi, Finland; P - Paakkila, Finland; K - Kamiah, Idaho.

Tremolite asbestos

Although there are numerous references to tremolite asbestos in the literature, relatively little of this fiber entered the world market. Probably the most famous reference to tremolite asbestos is to that from the Italian Alps, reportedly the asbestos of the Romans. Inquiry into this, however, leads one to believe that most of the asbestos fiber from the Alps was chrysotile, not tremolite.[3] Fibrous tremolite has not been reported in the recent and extensive literature on metamorphosed ultramafic rocks from north Italy, whereas chrysotile is often mentioned. Also, in a letter to Oliver Bowles, asbestos commodity specialist, U.S. Bureau of Mines (Bowles, 1937, p. 6), the chief mineral inspector in Rome stated in part:

"For a long time it was believed that the Italian 'amianti' were all the tremolite type because the first examinations of the material were based on samples of tremolite. It was only in recent years that, after further studies, the producers recognized that their products were for the most part chrysotile with a long, flexible fiber."

Tremolite asbestos has been mined in the Natal, South Africa, where it occurs in green talcose rocks -- probably altered ultramafic rocks similar to those of the Jamestown Series in the Barberton district of South Africa (Hall, 1918, p. 109). In the United States tremolite asbestos has been mined in small quantities near Powhatan and Pylesville, Maryland, where it occurs in amphibolized ultramafic rocks. Anthophyllite asbestos also occurs in these same rocks.

Actinolite, amosite, and crocidolite asbestos

Commercial mining of actinolite asbestos is practically unknown. No mining of amosite asbestos occurs outside the Transvaal. In the past crocidolite was mined in the Cochabamba, Bolivia, from rocks of igneous origin.

MAJOR OCCURRENCES OF CHRYSOTILE ASBESTOS

The commercially most important form of asbestos, chrysotile, is found in three distinct types of deposits: (Type I) alpine-type ultramafic rocks, including ophiolites, (Type II) stratiform ultramafic intrusions, and (Type III) serpentinized limestones. Type I deposits are by far the most important, furnishing at least 85 percent of the world's chrysotile fiber. Type III deposits are relatively unimportant but do furnish some high quality fiber.

Type I deposits

One example of a Type I deposit has already been discussed, the Paakkila and Maljasalmi fields of East Finland. In these deposits, however, the valuable asbestos mineral is anthophyllite, not chrysotile.

The two most important asbestos producing localities in terms of production, past and present, are the serpentinized ultramafic rocks of the central and southern Urals and of the Appalachian Mountains in southeast Quebec and northern Vermont. The Russian and North American occurrences are similar; the serpentinites are of the alpine-type and part of ophiolite sequences (Coleman, 1977).

The chrysotile asbestos deposits of Quebec, and their extension into northern Vermont, occur in altered peridotites, which form part of an ophiolite suite of rock types. Included in this suite, in addition to the peridotites (dunites and harzburgites), are gabbro cumulates, diabase sills, tholeiitic pillow lavas, and red argillites. These units were emplaced tectonically into the country rocks in early Ordovician time. The peridotites, regarded as fragments of oceanic crust and mantle, are suggested to have undergone the following sequence of events: (1) the formation of peridotites in an oceanic environment through lithosphere accretions and sea-floor spreading; (2) the fragmentation and tectonic emplacement; and (3) deformation of the ultramafic rocks within the Cambro-Ordovician country rocks (Laurent and Hébert, 1979). These same authors propose that serpentinization occurred in two stages: (1) early serpentinization in an oceanic environment at low temperatures, where lizardite was the principal serpentine mineral, and (2) late serpentinization in a dynamic regime of tectonic transport and emplacement, where fracturing of the peridotite masses took place. Chrysotile asbestos formed in these late-stage fractures, probably in a stress environment.

Chrysotile-bearing serpentinites form a part of a discontinuous belt of ultramafic bodies and associated rocks extending for almost the entire length of the Appalachian Mountain chain. The major and active chrysotile deposits are, however, centered in Quebec in the towns of Black Lake, East Broughton, Thetford Mines, and Asbestos; smaller active deposits are at Baie Verte, Newfoundland, and Eden Mills, north-central Vermont. Further south in the Appalachian Chain, the ultramafic bodies generally contain only small amounts of chrysotile; thus, only minor production of this fiber, with the exception of the Vermont Asbestos Group operation at Eden Mills, has occurred in the eastern United States. As already alluded to, these ultramafic rocks in Maryland, Virginia, North Carolina, and Georgia have been the sources of minor amounts of anthophyllite and tremolite asbestos.

The Quebec chrysotile deposits were first discovered in 1877 in the serpentine hills of Thetford and Coleraine. By 1900 this area had already produced 150,000 tonnes of chrysotile fiber; by 1980 nearly 40 million tonnes had been mined -- approximately 40 percent of the world's total asbestos production to that date. At present Quebec is the second leading producer of asbestos, approximately 1.4 million tonnes per annum, and is led only by the Ural areas of Russia, where the annual production is approximately 2.4 million tonnes.

The serpentinites associated with ophiolites within the Ural Mountain belt of the Soviet Union account for about 95 percent of the Russian production, all of which is chrysotile fiber. The two principal centers of production in the Urals are the Uralasbest complex, 90 km northeast of Sverdlovsk, and near Dzhetygara, in the southern Urals.

Other major Type I chrysotile asbestos deposits are found in the Italian Alps, the Troodos Mountains of Cyprus, and the Coalinga area of California. The classic asbestos deposits of north Italy are located in the Susa, Lanzo, Aosta, and Val Malenco areas of the Alps. These are areas underlain by metamorphosed ultramafic rocks of the alpine-type. At present the Balangero mine, located 30 km northwest of Turin in the Lanzo area, is the only operating asbestos mine in western Europe of any significance. The mine opened in 1916 and its present production is about 160,000 tonnes of chrysotile fiber per year.

The occurrence of asbestos on Cyprus may have been known many centuries ago, but significant production of chrysotile fiber began only in the 1920's. Production is now about 40,000 tonnes per annum. The deposits are in the Mt. Troodos Ophiolite Complex, one of the best studied ophiolite sequences in the world.

Near Coalinga, California, and located in the southern extension of the Diablo Range is a serpentinite dome exposed to the surface in an area 19.2x6.4 km and extending in depth to perhaps 4.5 km. This serpentine diapir consists of highly sheared serpentine minerals, which replaced the original olivine-orthopyroxene assemblage. The diapir probably formed by dismemberment of an ophiolite peridotite by tectonic forces, the sheared mélange moving upwards diapirically during subsequent orogenic events (Coleman, 1977, 1980; Mumpton and Thompson, 1975). The chrysotile asbestos is mined by several companies at Coalinga, but mining is sporadic and production is limited. Even though the ore runs up to 50 percent chrysotile (Quebec ore usually runs 3 to 6 percent), mining has lagged because of environmental controls and the shortness of the fibers (grades nos. 6 and 7). The reserves at Coalinga are tremendous; perhaps tens of millions of tonnes of short fiber are available near the surface, making Coalinga a vast resource for a type of asbestos which will be useful to strengthen plastics, tiles, etc.

Type II deposits of southern Africa

Whereas most of the chrysotile mined in the two major asbestos producing countries, Canada and the U.S.S.R., is from serpentinized ultramafic rocks within ophiolite sequences, almost all of the southern African production comes from Archean ultramafic stratiform complexes. These are generally associated with the ancient greenstone belts on the Rhodesian and Kaapvaal Cratons (Anhaeusser, 1976). Within the African greenstone belt, and particularly in the Lower Ultramafic Unit, a number of layered differentiated ultramafic pods and sills are developed which contain chrysotile fiber of economic importance. While age, stratigraphic, and genetic relationships of these Archean ultramafics are quite different from those of the ophiolites, both contain peridotite assemblages, including dunites, which have altered to chrysotile-bearing serpentinite.

South Africa and Swaziland. Here the two largest producers of chrysotile asbestos are the Msauli and Havelock mines, situated approximately 30 km southeast of Barberton, South Africa. The Havelock mine is situated just over the Transvaal border in Swaziland. These deposits are included within the Swartkoppie Formation, which straddles the Swaziland-Transvaal border. This formation includes green and gray schists, banded cherts, and a number of serpentine pods or lenses positioned in the same stratigraphic horizon. The serpentinized ultramafic inclusions are considered to represent parts of a once continuous or nearly continuous differentiated sill emplaced penecontemporaneously with the remaining Swartkoppie rocks and conformable with the latter (Anhaeusser, 1976). The other active chrysotile mines in South Africa occur in ultramafic bodies similar to those in the Msauli-Havelock area. Deposits located in Barberton Mountain Land of South Africa occur in the Stolzburg, Koedoe, Handsup-Mundt's Concession, Kaapsehoop, Kalkkloof, and

Rosentuin ultramafic bodies. Three small deposits are situated within the Muldersdrif ultramafic body about 25 km north of Johannesburg.

Chrysotile production in Swaziland for the year 1978 was 48,000 tonnes -- mainly from the Havelock mine. South African production of this fiber for 1978 was 113,000 tonnes and came from the Type II ultramafic deposits described above, as well as from Type III sedimentary deposits of the Carolina district.

Zimbabwe. The two principal chrysotile producing mines in Zimbabwe are located within the Mashaba and Shabani igneous complexes. The Mashaba complex occurs at the western end of the Fort Victoria greenstone belt in southern Zimbabwe. It is a layered ultramafic intrusion which includes pyroxenites and serpentinized dunites and harzburgites. The Shabani ultramafic body, located approximately 100 km west of Fort Victoria and immediately east of the Great Dyke, is a lenticular ultramafic sill and is suggested to have intruded into the Archean gneisses at the northeast margin of the Belingwe schist belt (Anhaeusser, 1976).

Small chrysotile deposits are found in the Filabusi ultramafic complexes located about 50 km west of the Shabani deposits and at the Ethyl deposit at the north end of the Great Dyke. The Great Dyke is an elongate mass of mafic and ultramafic rocks extending nearly 500 km across the Rhodesian Craton. It is not a true dike but rather the remains of four lopolithic intrusions. Chrysotile asbestos is found in the vicinity of faults where serpentinization apparently was promoted.

In 1978 the Zimbabwean chrysotile production was 210,000 tonnes, of which about 60 percent came from the Shabani and 35 percent from the Mashaba deposits.

Type III deposits

Commercially less important, yet geologically very interesting chrysotile deposits occur in serpentinized limestones; two notable localities are in the Globe area of central Arizona and in the Carolina area of the Transvaal.

The Arizona asbestos-bearing strata occur in the Precambrian Mescal limestone formations of the Apache Group, where diabase sills a few centimeters to a few meters thick have intruded. The commercial asbestos is developed by replacement of the limestones by serpentine, usually occurring within 40 meters of the diabase intrusion (Bateman, 1923; Stewart, 1961). Although only about 50,000 tonnes of chrysotile asbestos has been produced from Arizona from the time the deposits were opened early in this century to the present, the fiber is of very high quality and much sought after for applications in advanced technology.

An occurrence very similar to that in Arizona is found in the Transvaal Basin, where dikes and sills of diabase have intruded and altered the Malmani Dolomite. The principal asbestos deposits are located in eastern Transvaal west of Barberton Mountain Land and east of Carolina. The sills commonly produced a metamorphosed assemblage in the dolomite extending for a meter or more above the upper chilled contacts with the diabase. The controls on serpentine mineralization involve dedolomitization to calcite to furnish magnesium, solution of chert to furnish silica, and the presence of the diabase sill to furnish H_2O and heat (Anhaeusser, 1976). Fiber is not developed in chert-free dolomite but is seen replacing chert where present immediately above the sill.

As with the formation of amphibole asbestos discussed previously, it appears that in addition to the necessary chemical controls, a stress environment resulting from folding, faulting, or differential heating is required to promote the growth of chrysotile fiber. Anhaeusser (1976) suggests that the dominant regional controlling factor for asbestos development is folding.

HEALTH HAZARDS OF ASBESTOS

Diseases related to asbestos exposure

There are three principal diseases which are related to exposure to one or more of the commercial asbestos minerals. These are: (1) lung cancer, which includes cancer of the trachea, bronchus, and lung proper; (2) mesothelioma, a cancer of the pleural and peritoneal membranes which invest the lung and abdominal cavities, respectively; and (3) asbestosis, a diffuse interstitial fibrosis of the lung tissue often leading after long exposure to severe loss of lung function and respiratory failure. The lung cancer of asbestos workers is also associated with cigarette smoking, which leads to considerable difficulty in assigning relative risks of asbestos exposure to smokers. Mesothelioma, a disease which is usually fatal in one to two years after diagnosis, is rare, accounting for about 280 deaths per year in the United States and Canada. Of these deaths, there was a definite or a probable exposure to some form of asbestos in about 50 percent of the cases. Exposure to asbestos was unlikely in about 30 percent of the cases (McDonald and McDonald, 1980).

There are some epidemiological studies which suggest that asbestos workers may suffer excess cancer of the digestive tract (Selikoff and Lee, 1978); other studies do not support this conclusion (McDonald and McDonald, 1980; Meurman *et al.*, 1974; Rubino *et al.*, 1979; Nicholson *et al.*, 1979). There is still some question, then, as to the role played by asbestos in the etiology of digestive tract cancers. Becklake (1976), Selikoff and Lee (1978), and Simpson (1979) give complete reviews of the subject of asbestos and disease.

Although there seems to be no question that the residency of asbestos fibers within the lung and pleura for long periods of time can cause lung cancer, asbestosis, and mesothelioma, the exact mechanisms of disease production and the relative potencies of the different asbestos minerals are subjects of much study and many differences of opinion. By reviewing in the next section the health of miners exposed to specific minerals dusts and asbestos trades workers exposed to a variety of dusts, perhaps we can become more enlightened on this subject.

Particle size and shape appear to be the controlling factors with regard to whether mineral particles enter the lung and remain in the lung or are removed from the lung after entering. Particles such as asbestos fibers which have diameters greater than approximately 5 μm can not enter the bronchial airways[5]; those with smaller diameters do. Particles with diameters < 3 μm can penetrate to the smaller bronchioles and even to the alveolar sacs, the critical gas exchange portions of the lung. Most particles which enter the upper respiratory tract (the mainstem, bronchi, and bronchioles) are quickly and effectively removed by the mucocilliary

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[5]The airways of the lung form the bronchial tree, which is subdivided into the main stem and then into 22 additional branchings. The first several branchings constitute the bronchi, the last several the bronchioles. The terminal bronchioles lead to the respiratory bronchioles, which are lined with alveoli; the latter constitute the lower respiratory tract.

escalator; this is a system of mucous membranes and cilia lining the airways of the upper respiratory tract, which moves foreign particles upward to the pharynx, where they are unconsciously swallowed or spit out. A second lung clearance mechanism operates in the lower respiratory tract (the respiratory bronchioles and alveoli). Here pulmonary macrophages, or scavenger cells, engulf the foreign particles (phagocytosis) and then (1) move to the upper respiratory tract, where the mucociliary escalator is operative, or (2) move through the alveolar wall into the interstitium and eventually to the lymph channels.

Asbestos fibers which are longer than approximately 5 μm are not readily phagocytized by the macrophage cells and thus tend to remain in the lower respiratory tract, or they may penetrate the pleural membrane and enter the interpleural space. It is thought that when such fibers remain in the lung for lengthy periods of time, various biochemical reactions take place which promote the growth of interstitial collagen within the lung tissue, causing it to become fibrous with ensuing asbestosis. Long term residency of fibers in the lung and pleura also causes lung cancer and mesothelioma; the mechanisms by which this occurs are far from being understood.

Pleural cancer as we will see seems to be caused by crocidolite asbestos but not by chrysotile or anthophyllite asbestos. Lung cancer is caused by chrysotile, anthophyllite, amosite, and crocidolite asbestos in asbestos workers who smoke cigarettes. Evidence for excess lung cancer in non-smoking asbestos workers is weak. Two completely different substances, asbestos and cigarette smoke, combine to produce a very significant risk to many asbestos workers, particularly those who were heavily exposed to asbestos dusts.

Generally, asbestos-related diseases appear in asbestos workers only after many years have elapsed since first exposure. A significant increase in the lung cancer death rate appears 10 to 14 years after first exposure and peaks at 30 to 35 years. The mesothelioma death rate becomes significant 20 years after first exposure but continues to climb even after 45 years have elapsed. The asbestosis death rate becomes significant 15 to 20 years after first exposure and apparently peaks at 40 to 45 years (Selikoff *et al.*, 1980a).

Epidemiology

Before considering the mortality studies of the various occupational groups exposed to asbestos, it is useful to briefly consider the roles the three important types of asbestos (amosite, crocidolite, and chrysotile) have played in the commerce of North America and Europe, the areas where the major epidemiological studies of asbestos workers were made.

In North America, chrysotile entered the market in large quantities early in this century. Crocidolite was apparently first used in the United States in 1912 when 9 tonnes was imported, but it was not until World War I that its use for high temperature insulation became established -- particularly in the ship building industry. By 1930 nearly 32,000 tonnes of crude crocidolite fiber had been imported into the United States (*Mineral Resources of the United States*, 1907...1929, U.S. Dept. Interior, Washington, D.C.). It was not until the mid 1930's that amosite asbestos gained a market in North America when it began to replace crocidolite for high temperature insulation. Crocidolite was milled in Bound Brook, New Jersey, in 1920, and in 1924 the operation moved to larger facilities in Millington, New Jersey. The many advertisements in the trade journal *Asbestos* during the period 1920 to 1945 indicate that crocidolite was used in many products and particularly for insulation of steam boilers, locomotives, and pipes. As an example, a product containing crocidolite asbestos and called "85% Magnesian Sectional Pipe Covering" was advertised monthly in *Asbestos* from 1920 to 1945 (see also McCullagh, 1980). Amosite, crocidolite, and chrysotile were almost universally used aboard ships during World War II, amosite for high temperature boilers and pipes, crocidolite for packings exposed to acids or salt water, and chrysotile for low temperature and electric insulation.

The use of asbestos in Europe paralleled that in North America, with one notable exception -- the extensive use in Europe of crocidolite asbestos as a sprayed-on coating to fireproof ships[6], railroad cars,

[6]Mesothelioma is prevalent in the shipyard workers of Europe; at Walcheren, Wilhelmshaven, Plymouth, Trieste, Hamburg, Nantes, Rotterdam, and Malmö (McDonald and McDonald, 1977). The extensive use of crocidolite aboard European ships prior to and during World War II is suggested to be an important factor in the etiology of this disease.

buildings, etc. Sprayed-on coatings were also used in the United States after World War II, but the coatings contained, with few exceptions, chrysotile rather than crocidolite. Sprayed-on asbestos coatings were not used on U.S. ships, the principal use being to fireproof steel building girders and as acoustical coatings in schools and offices.

Asbestos trades workers. A very significant increased incidence, relative to the general male population, of lung cancer, asbestosis, and mesothelioma is found in men who were employed in the "asbestos trades" -- the insulation of steam locomotives, boilers, ships, and buildings; and the fabrication and installation of asbestos-containing textiles, roofing materials, cement products, tiles, wallboards, brake linings, clutch facings, filters, packings, gaskets, etc. Those in the "trades" generally used several types of asbestos minerals during their working careers; most commonly these were chrysotile, crocidolite, and amosite, and rarely anthophyllite. Significant exposures of any group of workers, at least for the past fifty years, to tremolite or actinolite asbestos dusts has probably not occurred.

Thirteen major mortality studies of asbestos trades workers are presented in Table 4; five of these are of workers engaged in the asbestos insulation trades, and eight are of workers in the factory and textile trades. Most of the workers are male, a few are female. In all, 38,904 individuals were followed; of these, 5,450 have died, including 998 (18.3 percent) who died of lung cancer and 327 (6.0 percent) who died of mesothelioma. In the thirteen studies the lung cancer mortality varied from 6.1 to 24.5 percent of all deaths; mesothelioma mortality varied from 0 to 9.5 percent of all deaths. The workers involved in studies nos. 1 through 12 worked with more than one form of asbestos; those in study no. 13 worked only with chrysotile asbestos.

Estimates of expected cancer mortality are very difficult to predict, because cancer rates are modified by the individual's "lifestyle," as well as by occupation. The major "lifestyle" contribution to lung cancer is cigarette use. To better assess the significance of these health studies, it is necessary to examine the cancer mortality patterns of cigarette smokers who were not exposed to asbestos dusts. Unless prevalence of smoking within the study group is carefully evaluated, it is impossible to predict accurately the health effects of occupational exposure to carcinogens such as asbestos, radon gas, and arsenic. Unfortunately, in only a few of the studies listed in Table 4 have adequate assessments been made of the proportion of workers who smoke cigarettes.

The contribution of cigarette smoking to the increased incidence of disease has been evaluated in several studies and has led to a consensus that this habit produces a very significant increase in risk of dying of lung cancer, as well as of the various cardiovascular diseases. The largest study of cigarette smokers is that of E. Cuyler Hammond and colleagues under the auspices of the American Cancer Society. This study is based on questionnaires and mortality follow-up accomplished between July 1960 and June 1971 for approximately 51,000 men (Hammond *et al.*, 1978). The proportional mortality of lung cancer (percent lung cancer deaths relative to deaths by all causes), based on the Hammond study, is shown graphically in Figure 7. For a group of men who all smoke cigarettes (cohort of 100 percent smokers) lung cancer mortality is approximately 7 percent at age 45, reaches a maximum of approximately 10 percent at age 70, then decreases slightly at older ages. For a cohort of male non-smokers, lung cancer mortality is 2 percent at age 45 and then decreases continuously to approximately 1 percent at age 95.

Smoking is most prevalent in blue-collar occupations relative to professional and managerial occupations (Sterling and Weinkam , 1978). This prevalence also holds true for the asbestos trades, mining, and milling occupations. In a group of 13,722 asbestos insulation workers whose smoking habits were recorded, 70 percent had a history of cigarette smoking (Selikoff and Hammond, 1975; Saracci, 1977). In a group of 1,015 chrysotile asbestos miners and millers, 85 percent were smokers (McDonald *et al.*, 1974). Data given in Figure 7 predicts that the lung cancer mortality for a cohort composed of 75 percent smokers would be at least 6 to 7.5 percent, regardless of occupation. In Table 4 we see that the lung cancer mortality for the total of 13 cohorts of asbestos "trades" workers was 18.3 percent -- approximately three times that expected if mortality predictions were based only on the apparent smoking habits.

The increased risk of lung cancer due to asbestos exposure in non-smokers is very low (Saracci, 1977). There appears to be no relationship

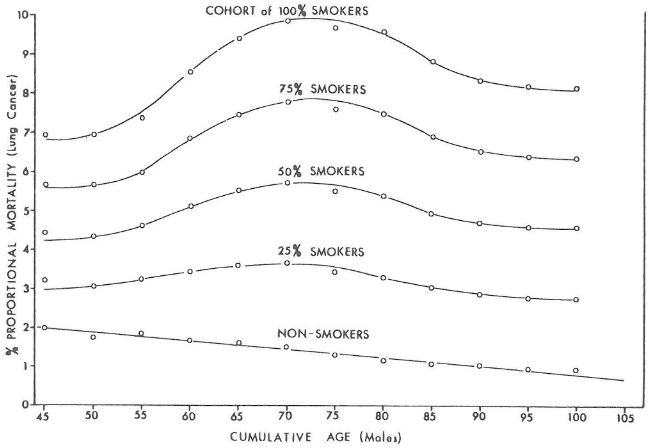

Figure 7. Percent of lung cancer deaths in males relative to deaths by all causes (proportional mortality - lung cancer) plotted with respect to age for four groups (cohorts) with different cigarette smoking characteristics and for a cohort of non-smokers. For example, for a cohort of 70-year old males which is composed of 75 percent cigarette smokers, 7.8 percent of all deaths at age 70 are predicted to be from lung cancer. Graphical presentation based on data from Hammond *et al.* (1978).

Table 4. Cancer mortality for men working in the asbestos "trades"

Study No.	Ref.1/	Occupation	No. in cohort	No. deaths	Lung cancer No.	(%)3/	Mesothelioma No.	(%)3/
1	(A)	Insulators, NY-NJ (1943-74)	632	451	89	(19.7)	35	(7.8)
2	(B)	Insulators, U.S., Canada (1967-76)	17800	2270	485	(21.4)	175	(7.7)
3	(A)	Factory, N.J. (1941-74)	933	483	83	(17.2)	10	(2.1)
4	(C)	Insulators, U.S. (1967-71)	7289	446	79	(17.7)	23	(5.2)
5	(B)	Factory, U.S. (1959-75)	689	274	35	(12.8)	26	(9.5)
6	(D)	Factory, England (1931-74)	1106 2/	317	51	(16.1)	10	(3.2)
7	(E)	Insulators, N.Y. (1945-65)	152	46	10	(21.7)	3	(6.5)
8	(F)	Insulators, Belfast (1940-66)	170	98	24	(24.5)	7	(7.1)
9	(G)	Textiles, London (1931-70)	6760	350	63	(18.0)	24	(6.9)
10	(H)	Factory, Cardiff (1936-62)	1165	133	11	(8.3)	1	(0.8)
11	(I)	Factory, Penn. (1938-64)	1265	330	35	(10.6)	8	(2.4)
12	(J)	Textiles (1933-74)	679	186	29	(15.6)	5	(2.7)
13	(K)	Factory, U.S.A. 4/ (1945-74)	264	66	4	(6.1)	0	0
Total of cohorts			38904	5450	998	(18.3)	327	(6.0)

1/ References: (A) Selikoff, 1977; (B) Nicholson et al., 1978; (C) Selikoff et al., 1973; (D) Peto et al., 1977; (E) Kleinfeld et al., 1967; (F) Elmes and Simpson, 1971; (G) Newhouse, 1973; (H) Elwood and Cochrane, 1964; (I) Mancuso and El Attar, 1967; (J) Peto, 1978; (K) Weiss, 1977.

2/ includes 284 women

3/ percent of all deaths (proportional mortality)

4/ workers were exposed only to chrysotile asbestos between smoking habits and the incidence of mesothelioma; this disease is equally prevalent in smokers and non-smokers alike. Of the studies listed in Table 4, only Study no. 13 of chrysotile factory workers shows a lung cancer mortality that would be expected from the smoking habits alone.

Asbestos miners and millers. Men working in the mining and milling of asbestos ore are generally exposed to only one form of fiber. A few exceptions occur in the mining regions of South Africa, where some workers have been employed in crocidolite, amosite, and chrysotile mines. Anthophyllite and tremolite asbestos miners may have been exposed to some chrysotile asbestos, because these minerals can coexist in metamorphosed ultramafic rocks, for example those of Paakkila, Finland, and Kamiah, Idaho.

Epidemiological studies of asbestos miners and millers who were exposed to only one form of asbestos are useful for understanding how the different asbestos minerals affect human health. In Table 5 are given the mortality data for the five major epidemiological studies of asbestos miners and millers. In addition, three studies are given of miners exposed to cummingtonite and grunerite amphibole dusts and one study of tunnel workers exposed to hornblende amphibole dust. Some classify these amphiboles as asbestos, even though they do not possess the physical properties requisite to be valuable commercially. Such a classification has been made in the case of taconite mining by the courts (United States District Court for Minnesota, 380 F. Supp. 11) and by the U.S. Environmental Protection Agency (Reserve Mining *vs* EPA, U.S. Court of Appeals Eighth Circuit, March 14, 1975), which has sued to prevent the Reserve Mining Company from dumping taconite tailings into Lake Superior because of the perception that these tailings contain "amosite asbestos" and thus constitute a threat to public health. For a complete review of the case, see 514 Federal Reporter, 2d Series, 492-542, 1975; 256 North Western Reporter, 2nd Series, 808-852, 1977. Of interest regarding this suit are the health studies accomplished on the Reserve iron ore miners exposed to cummingtonite and grunerite in the taconite rock (Table 5, Study II) and on the Homestake gold miners exposed to

Table 5. Mortality from selected causes in the principal epidemiological studies of commercial asbestos miners and millers and other hard rock miners and tunnel workers exposed to rock dust containing minerals sometimes defined as asbestos[1]

Cause of Death[2]	Number of Deaths	Study I 900 men 1936-1967	II 5751 men 1952-1976	III 932 men 1955-1972	IV 440 men 1960-1973	V 1321 men 1937-1973	VI -- 1943-1977	VII 933 men 1946-1975	VIII 544 men 1961-1977	IX 10939 men 1910-1975	Totals (excluding Study VI)
All causes (000-999)	Observed	216	298	294	71	631	519	332	178	4463	6483
	Expected		344	225	52.9	549.7	600.3	214.4	159.9		
	Obs./Exp.		0.87	1.30	1.34	1.15	0.86	1.55	1.11		
Respiratory cancer (162)	Obs.	21	15	21	10	16	60	10	28	250	371
	% all deaths	9.7	5.0	7.1	14.1[3]	2.5	11.6	3.0	15.7	5.6	5.7
	Exp.	12.6	17.9	13.15	2.7	16.5	38.9	10.4	11.1		
	Obs./Exp.	1.67	0.84	1.60	3.0	0.97	1.54	0.96	2.5		
Mesothelioma, peritoneum, pleura (58,163)	Obs.	0	0		0	1?	17	1?	1	10[5]	11 + 2?
	% all deaths	0	0		0	0.16?	3.3	0.30?	0.56	0.22	0.17+0.03?
Gastro-intestinal cancer (150-154) or (150-159)	Obs.	7	20	10		39		19	10	168	273
	% all deaths	3.2	6.7	3.4		6.2		5.7	5.6	3.8	4.2
	Exp.	14.9	17.6	11.13		35.1		19.3	9.5		
	Obs./Exp.	0.47	1.14	0.90		1.11		0.98	1.05		
Pneumoconiosis (500-519)	Obs.		4[7]	20	5	37	21[1]	20	30	46[6]	
	% all deaths		1.3	6.8	7.0	5.9	4.0	6.0	16.9	1.0	
Asbestosis (501)	Obs.	13						9	26		
Silicosis (502)	Obs.					35					
Respiratory tuberculosis (011-012)	Obs.	36		11		39	4	18		248	
	% all deaths	16.7		3.7		6.2	0.77	5.4		5.6	
Locality		North Savo, Finland	Minnesota, U.S.A.	Manhatten I. N.Y., U.S.A.	Lead, ND, U.S.A.	Lead, ND, U.S.A.	Wittenoom, W. Australia	Balangero, Italy	Quebec, Canada	Quebec, Canada	
Type of Mining		asbestos	iron ore	tunneling	gold	gold	asbestos	asbestos	asbestos	asbestos	
Type of Rock		ultramafic	taconite	schist, gneiss, amphibolite	qtz-cummingtonite schist	qtz-cummingtonite schist	banded ironstone	serpentinite	serpentinite	serpentinite	
Suspected mineral pathogen		anthophyllite asbestos	cummingtonite, grunerite, quartz	hornblende, quartz	cummingtonite, hornblende, quartz	cummingtonite, hornblende, quartz	crocidolite asbestos, quartz	chrysotile asbestos	chrysotile asbestos	chrysotile asbestos	
Source		Meurman et al., 1974	Higgins, 1981	Selikoff, 1978	Gillam et al. 1976	McDonald et al., 1978	Hobbs et al., 1980	Rubino et al., 1979	Nicholson et al., 1979	McDonald et al., 1980	

1/ Cummingtonite, grunerite, and hornblende (Studies II, III, IV, V) may be defined as "asbestos" in U.S. Federal Regulations.
2/ International Classification of Diseases, 9th revision (ICD·9·CM), January 1, 1979.
3/ Includes one carcinoma of the maxillary sinus and one mediastinal carcinoma (unspecified). See footnote 7/ in text.
4/ Pneumoconiosis Board Records (Western Australia) show pneumoconiosis of mixed type, asbestosis, silico-asbestosis, and silicosis.
5/ Two mesothelioma victims worked with crocidolite in addition to chrysotile.
6/ Pneumoconiosis is probably predominantly asbestosis since rock dust contains little crystalline silica (quartz, etc.)
7/ "Selected respiratory disease"

cummingtonite in the gold-bearing schists (Table 5, Study IV, V).[7] Studies II and V show no evidence of asbestos-related diseases appearing in the study groups.

Mortality comparisons, trades vs. mines. The cancer mortality pattern for those in the asbestos trades and mining occupations is graphically presented in Figure 8, where lung cancer mortality is plotted with respect to mortality due to mesothelioma. The studies of the

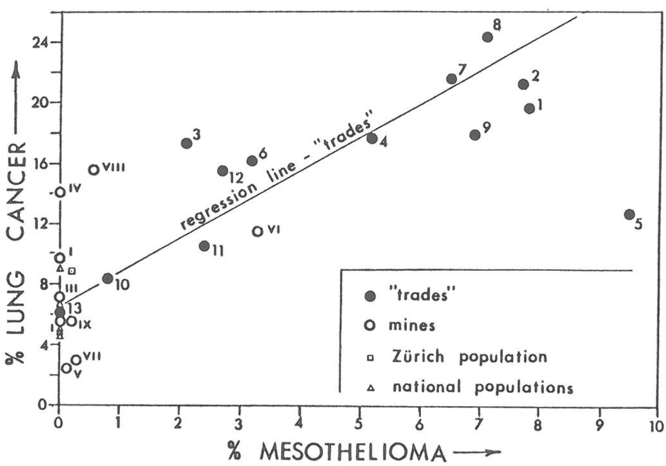

Figure 8. Graphical comparison of the proportional mortality due to lung cancer and mesothelioma for the asbestos trades workers ("trades," Table 4, Studies 1-13), the asbestos miners and millers ("mines," Table 5, Studies I-IX), the male population of the Zürich area of Switzerland, and the male populations of five nations (Table 6). Regression analysis of the mortality of the asbestos trades workers (Studies 1-4, 6-13) shows a positive correlation between the two diseases; 78 percent of the variance ($\bar{r}^2$) of lung cancer is accounted for by mesothelioma. The regression line is of the form: y(mesothelioma) = -2.94 + 0.446x (lung cancer). The intercept at y = 0 is 6.6 percent lung cancer, a reasonable estimate of mortality for this disease if the asbestos trade workers had never worked with asbestos but had retained their smoking habits.

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[7] Study V (McDonald *et al.*, 1978) discredits Study IV (Gillam *et al.*, 1976). Study IV was accomplished on a sub-cohort of the Study V cohort. The latter study is much more complete; statistically it is based on 631 deaths, whereas Study IV is based on 71 deaths. In addition, Study IV presents an implausible mortality pattern: (1) No deaths due to silicosis, tuberculosis, or silico-tuberculosis were reported, despite the fact that the mining company has been coping with a quartz dust problem for a century, and (2) a 14·1 percent respiratory cancer mortality (incorrectly included as respiratory cancer were a sinus and a mediastinal carcinoma) was attributed to "cummingtonite asbestos," yet no mortality due to asbestosis was reported. The cummingtonite found in the quartz-cummingtonite schist host rock is not asbestos, but rather garden-variety, rock-forming amphibole.

asbestos trades workers (Table 4; Fig. 8, solid circles) show a very significant excess of mortality due to mesothelioma relative to that found in the miners (Table 5, Fig. 8, open circles) -- with one exception, the crocidolite miners of Western Australia (Study VI). For the asbestos trades workers a disease correlation is evident. Neglecting Study 5 (Table 4, Fig. 8), which is somewhat anomalous, regression analysis of the twelve trades data points (Studies 1-4, 6-13, Table 4, Fig. 8) shows a positive correlation between lung cancer and mesothelioma mortality; 78 percent of the variance ($\bar{r}^2$) of lung cancer is accounted for by mesothelioma. Part of the remaining variance (22%) can be accounted for by inter-cohort differences in prevalence of cigarette smoking. This is because the smoking habits of asbestos workers seem to greatly influence the lung cancer incidence but not mesothelioma incidence.

In regard to high mesothelioma mortality, it is important to note the health studies of two groups of specialized factory workers who, during World War II, were employed at the task of placing crocidolite filter pads into gas mask canisters. One group working in Canada, composed of 109 men and 90 women, suffered 12.5 and 16.1 percent lung cancer and mesothelioma mortality, respectively (McDonald and McDonald, 1978). A second group of 1600 people, mostly women, were employed at this same task at a factory in Nottingham, England. Jones *et al.* (1976) reported that 26 mesothelioma deaths have occurred in this group; 25 were women. A large number of workers in these two groups were exposed to asbestos only during this brief World War II work period. The high proportion of women with their more moderate smoking habits in the gas mask worker cohorts would suggest that the ratio of mesothelioma to lung cancer (1.3 for the Canadian group) would be higher than that observed in the more typical "trades" cohorts (Table 4), where the ratio averages 0.44 (Fig. 8).

With the exception of the crocidolite miners (Study VI), the mortality patterns of the hardrock miners (Studies II, V), the tunnel workers (Study III), the asbestos miners (Studies I, VII-IX), and the chrysotile factory workers (Study 13) is quite different from that of the "trades" (Studies 1-12). The most apparent difference between the "trades" cohorts and these miners, tunnel workers, and chrysotile factory workers is the relative incidence of mesothelioma. The latter groups, composed of individuals who did not come into contact with crocidolite, have very low mesothelioma mortality.

To make further comparisons it is useful to examine the mortality with respect to lung cancer and mesothelioma in national populations. In Table 6 are given the lung cancer and mesothelioma mortality of all males over 24 years of age in five nations. These data are plotted in Figure 8. We find that the average lung cancer mortality of these five national populations is 5.7 percent, a figure identical to the 5.7 percent average mortality of the miners and tunnel workers (Table 5, excluding crocidolite miners). The mesothelioma mortality of the five national populations is 0.03 percent (Table 6) and is probably significantly underreported because of (1) the great difficulty in diagnosing this disease, even after autopsy (McDonald and McDonald, 1977, 1980; Vejlsted and Hansen, 1980; Kannerstein and Churg, 1980; Legha and Muggia, 1977) and (2) complications arising in properly and consistently coding this disease for later information retrieval.

Table 6. Cancer mortality in men over 24 years of age for 5 nations (McDonald and McDonald, 1977)

Nation	Deaths (year)	Lung cancer No.(%)1/	Mesothelioma No.(%)1/
England-Wales	278,617 (1970)	24913 (8.9)	154 (0.06)
Finland	22,332 (1970)	1586 (7.1)	8 (0.04)
Italy	272,795 (1970)	11867 (4.7)	not reported
U.S.A.	988,620 (1969)	50481 (5.1)	250 (0.03)
Canada	82,052 (1970)	4312 (5.3)	25 (0.03)
Totals	1,624,416	93159 (5.7)	437 (0.03)

1/ percent of all deaths (proportional mortality)

It is more meaningful to compare mesothelioma mortality among asbestos workers and miners in whom this disease is looked for to the mortality in a population where the causes of death are based on a large number of autopsies and where asbestos exposure is minimal. A review has been made by Rüttner (1978) of the deaths in the Zürich area of Switzerland, where there are no asbestos mines, mills, or industries and where the cause of death is often based on autopsy. Among the 28,110 male deaths (all autopsied) over the period 1961 to 1976, 51 deaths were due to mesothelioma (0.18 percent) and 2466 were due to lung cancer (8.8 percent). Among women (22,583 deaths) 23 were caused by mesothelioma (0.10 percent) and 368 caused by lung cancer (1.6 percent). The proportional mesothelioma mortality for hard-rock miners, tunnel workers, and asbestos miners (other than crocidolite) is 0.17 to 0.20 percent (Table 5). The asbestos trades workers, by contrast, have an average mesothelioma mortality of 6.0 percent (Table 4).

Among the asbestos miners and millers there is no question that those exposed to heavy concentrations of chrysotile and anthophyllite dust over long periods of time have suffered a significant excess mortality due to lung cancer and asbestosis -- but not to mesothelioma (Studies I, VIII, Table 5). The most detailed health study of asbestos miners to date is that of the chrysotile asbestos miners of Quebec (Table 5, Study IX). Here McDonald *et al.* (1980) have carefully documented the relationship between lung cancer incidence and cumulative dust exposure. The average dust concentrations that the miners and millers experienced during the working day were divided into four categories depending on the work tasks performed during their careers in the mines: low level 2.5 to 4.2 mpcf[8], medium level 4.3 to 9.4, high level 14.4 to 23.6, and very high level 46.8 to 82.6 mpcf. The mean within these four categories in terms of chrysotile fibers per cm^3 is: low 10 fibers/cm^3, medium 21 fibers/cm^3, high 95 fibers/cm^3, and very high 194 fibers/cm^3. For the men exposed for over 20 years in the low and medium dust categories (averaging 6.6 mpcf or approximately 20 fibers/cm^3), total mortality was less than expected (SMR = 0.94).[9] For

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[8]mpcf = millions of particles of rock dust per cubic foot. Conversions of this figure into asbestos fibers per cubic centimeter, the usual measurement for industrial hygiene monitoring, is difficult, but an approximate and conservative figure is: 1 mpcf = 3 fibers/cm^3 (McDonald *et al.*, 1980, p. 21, 23; see also McDonald *et al.*, 1976).

[9]SMR (standard mortality ratio) = number of deaths expected in a cohort at risk divided by the number of deaths in a cohort not at risk (control cohort). "Standard" implies that the control cohort does not differ in a way from the cohort at risk other than exposure to a

these men there was a slight excess risk of lung cancer (SMR = 1.15) and respiratory tuberculosis (SMR = 1.14). Since exposures of 20 fibers/cm^3 are an order of magnitude higher than that experienced now (dust levels for the past few years have been maintained at less than 2 fibers/cm^3), miners working a lifetime under the present dust levels are not expected to present any significant health problems relative to those in other mining industries.

McDonald *et al.* (1980) have also studied the health statistics of a cohort of 440 women who also worked in the Quebec chrysotile asbestos mines and mills. Of the 84 who have died, there was one death due to lung cancer and one due to mesothelioma.

Crocidolite exposure. There is persuasive data, much already surveyed, which shows that crocidolite asbestos is much more hazardous than chrysotile, anthophyllite, and amosite. Of the mining populations of the world only those in the crocidolite mining area of the Cape Province of South Africa and at Wittenoon Gorge, Western Australia, have a statistically significant increase in mortality due to mesothelioma. Also, mesothelioma deaths have been reported among the residents of these areas who are not employed in the mines or mills. For example, Webster (1978) reports that the South African Asbestos Tumour Reference Panel placed 712 cases of mesothelioma on the register, which included all the known cases since 1956. Of these, occupational and environmental background was established for 420 cases. Actual mining exposure accounted for 139 of the 420 cases, of which 120 were in connection with Cape crocidolite mining and two with Transvaal crocidolite mining. There were only four mesothelioma cases in those associated with amosite mining, and two of these had been exposed to Cape crocidolite as well. In the chrysotile mining industry there was only one case -- a miner from Rhodesia. Of the 100 environmental cases (those not employed in any occupation where asbestos is used), 93 had been exposed to Cape crocidolite, two to Transvaal crocidolite, and one possibly to amosite.

Additional prevalence studies in the Cape Province (Talent *et al.*,

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particular occupational or lifestyle hazard. SMR's are useful to compare total mortality as well as mortality related to a particular disease or accident *provided* a proper control cohort can be chosen.

1981) discovered 65 active cases of mesothelioma in people who had presented themselves for medical examination. Fifteen of these cases appeared in two groups, numbering 755 and 947 individuals, who were once employed in the crocidolite mines. An additional thirty-eight mesothelioma cases appeared in a survey of certain patients at the St. Michael's Hospital in Kuruman, Cape Province, who were not responding to treatment for suspected pulmonary tuberculosis. Fourteen of these mesothelioma patients were known to have worked in the crocidolite asbestos mines. Lastly, 12 of the 65 cases appeared in a medical survey of 53 females who, in the past, had hand-cobbed crocidolite asbestos.

In contrast to the prevalence of mesothelioma in the Cape Province, this disease is very rare in the Transvaal, where all of the world's amosite is mined. Wagner *et al.* (1960), in regard to their initial discovery of the association of crocidolite asbestos with mesothelioma, state (p. 260) "the tumour (referring to mesothelioma) is rarely encountered elsewhere in South Africa. During the past five years, with the exception of the present series (in Cape Province), no neoplasm of this nature has been diagnosed amongst 10,000 lungs examined at the Pneumoconiosis Bureau in Johannesburg, or in the Pathology Department of the South African Institute for Medical Research. Higginson and Oettle (1957) did not observe a single case in their survey of malignant tumours occurring in the Bantu and Cape Coloured population of Johannesburg and the North Eastern Transvaal."

The incidence of mesothelioma in Zimbabwe (Rhodesia), a country which is a major producer of chrysotile but mines no other form of asbestos, is very low. In a communication to Mostert and Meintjes (1979), the Secretary of the Rhodesia Pneumoconiosis Board stated that no cases of mesothelioma were reported in the mining industry. It is of interest to note that two cases of mesothelioma were reported in the Rhodesian railway industry, a locomotive engineer and a storeman. The locomotives were insulated with crocidolite asbestos to which these two men were exposed (Mostert and Meintjes, 1979). Cochrane and Webster (1978) report 12 cases of mesothelioma in men employed as insulators in the locomotive workshops of the South African Railways.

The prevalence of mesothelioma among the miners of Wittenoon Gorge has been discussed (Table 5, Study VI). The town of Wittenoon, the center of crocidolite mining in Western Australia, reached a peak population of about 1,000 in the 1960's. At present the population is down to about 200 and the West Australian State Government has suggested the closing of the town and evacuation of the residents because of continuing risks of airborne asbestos dust (*Chemical Week*, December 8, 1978, p. 25). The risk of mesothelioma among the residents of the town who were not employed by mines is demonstrated by the case of a 27-year-old woman who had an environmental childhood exposure to crocidolite (Langlois *et al.*, 1978).

SUMMARY

Production

Of the six forms of asbestos, only four have been used to any significant degree in commerce. These are amosite, crocidolite, anthophyllite, and chrysotile. Although asbestos was used by Stone Age man, it was not until the latter part of the 19th century that it came into widespread use in the industrialized world. The modern industry began in Italy and England after 1860, with Quebec being the main supplier of the crude fiber. By 1900 two to three hundred thousand metric tonnes had been mined, mostly in Quebec. By 1980 over 100 million tonnes had been mined worldwide of which about 90 percent was of the chrysotile variety. Approximately 75 percent of all asbestos ever mined has come from just three chrysotile mining localities, Quebec, Canada, and the central and southern Urals of the Soviet Union. The chrysotile producing countries in order of importance are the Soviet Union (46.1 percent of the world's total asbestos production in 1978), Canada (28.9%), Zimbabwe (3.8%), China (3.8%), Italy (2.9%), South Africa (2.1%), Brazil (1.8%), U.S.A. (1.7%), and Australia (1.0%).

Two to three percent of the world's asbestos production has been the crocidolite variety, most of which came from South Africa. Western Australia was a minor producer of crocidolite between 1944 and 1966. All amosite has been mined in the Transvaal Province of South Africa and accounts for about two to three percent of all asbestos ever produced. The only significant anthophyllite production came from Finland, where 350,000 tonnes was mined between 1918 and 1966. Total production of anthophyllite asbestos probably accounts for no more than 0.5 percent of the world's total asbestos production to date.

Geology

Deposits of commercial asbestos are found in four types of rocks: (I) alpine-type ultramafic rocks, including ophiolites (chrysotile, anthophyllite, and tremolite); (II) stratiform ultramafic intrusions (chrysotile and tremolite); (III) serpentinized limestone (chrysotile); and (IV) banded ironstones (amosite and crocidolite). Type I deposits are by far the most important and probably account for over 85 percent of the asbestos ever mined. The most important Type I deposits are those of Quebec and the Urals.

Type II deposits are found mostly in South Africa, Swaziland, and Zimbabwe. These furnish mostly chrysotile asbestos. Type III deposits are small in size; the most notable of these are located in Globe, Arizona, and in the Carolina area of the Transvaal Province of South Africa. Type IV deposits are found only in the Precambrian banded ironstones of the Transvaal and Cape Provinces of South Africa and of Western Australia. Only the South African deposits are still in production.

There is considerable geologic evidence that commercial asbestos deposits form only where there is a favorable stress environment, such as where folding or faulting occurs.

Asbestos and health

The three principal diseases which are related to asbestos exposure are (1) lung cancer, (2) cancer of the pleural and peritoneal membranes (mesothelioma), and (3) asbestosis, a condition in which the lung tissue becomes fibrous and thus loses its ability to function. Lung cancer can be caused by exposure to chrysotile, anthophyllite, amosite, and crocidolite asbestos; however, increased risk of this disease is probably found only in those who also smoke cigarettes. Asbestosis is also caused by heavy and prolonged exposure to all four forms of asbestos. Mesothelioma is caused principally by exposure to crocidolite asbestos. There is good evidence that anthophyllite and chrysotile asbestos do not cause any significant increase in mesothelioma mortality, even after heavy exposure for many years. Thus far only about 10 or 12 deaths among anthophyllite and chrysotile miners have been attributed to this disease.

There is some question as to the relationship between exposure to amosite asbestos and incidence of mesothelioma. Transvaal amosite miners seem not to show this disease, whereas, according to I.J. Selikoff and coworkers, fourteen men exposed to amosite during World War II at a Patterson, New Jersey, factory have died of pleural or peritoneal mesothelioma (Selikoff *et al.*, 1980b). It should be noted, however, that only one mesothelioma case was noted on the death certificates. The thirteen other deaths were recorded by Selikoff from a postmortem "best estimate." Such "adjustments" of death certificate data make it impossible to compare different epidemiological studies or to compare to "control" groups. In addition, there are two other observations relating to amosite asbestos that Selikoff does not address: (1) the very low mesothelioma rates in the Transvaal amosite miners and (2) the strong possibility that many of the Patterson factory amosite workers had previous work experience in New Jersey factories that processed crocidolite asbestos. McCullagh (1980) in a review of the Patterson workforce suggests that "something like one-third, or some 300 members, of the Patterson cohort may have been occupationally exposed to asbestos before entering the cohort."

Chrysotile asbestos, which accounts for about 95 percent of the asbestos in the present market, is much less harmful to miners than is crocidolite and probably amosite. McDonald *et al.* (1980) found that for men exposed for over 20 years to chrysotile dust averaging 20 fibers/cm^3, the total mortality was less than expected (620 observed deaths, 659 expected deaths). Risk of lung cancer was slightly increased: 48 deaths observed, 42 deaths expected. Exposures to 20 fibers/cm^3 are an order of magnitude greater than those experienced now (generally less than 2 fibers/cm^3); thus, chrysotile miners working a lifetime under these present dust levels should not be expected to suffer any measureable excess cancer.[10]

[10] If there is no threshhold below which there is a zero risk of developing cancer from exposure to a carcinogen (many believe such a threshhold exists, many do not), then even exposures to chrysotile

Epidemiological evidence does not exist to assess the health effects of tremolite or actinolite asbestos. The minerals cummingtonite, grunerite, and hornblende, which are sometimes considered to be asbestos-like, have been shown not to cause asbestos diseases in miners.

ACKNOWLEDGMENTS

I thank David B. Stewart for a helpful review of this paper.

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asbestos as low as two fibers per cubic centimeter could cause a few cancers to develop within a significantly large work force. Yet, the same also can be said of the human cost of operating heavy mining and manufacturing machinery; there will be some accidents resulting in injury and loss of life no matter how carefully the safety procedures are designed and followed. If, as some propose, society is to abandon the use of chrysotile asbestos despite the optimistic health picture for the present Quebec asbestos miners and millers, we should first be able to answer these questions:

(1) What will the health risk be to those exposed to the asbestos substitutes?

(2) Will the substitutes be less effective for fire protection, for braking efficiency, and for strengthening materials, resulting in increased injury and loss of life?

(3) Will the costs of the substitutes prevent their use, for example, as replacement material for asbestos in cement water pipe and reinforced construction cement?

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