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P.O. Box 9140
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History of asbestos discovery and use and asbestos-related disease in context with the occurrence of asbestos within ophiolite complexes

Malcolm Ross*
Robert P. Nolan*
Earth and Environmental Sciences of the Graduate School and University Center of The City University of New York,
365 Fifth Avenue, New York, New York 10016, USA

ABSTRACT

Two ancient asbestos mines, one near Karystos, Greece, and the other southeast of Mount Troodos, Cyprus, were located in what we now know to be ophiolite terrane. Evidence suggests that asbestos was discovered and utilized in Cyprus, perhaps as long as 5,000 years ago, for manufacture of cremation cloths, lamp wicks, hats, and shoes. Some of the adverse health effects of asbestos became known only in the early twentieth century, but it was not until the 1960s that the asbestos-related diseases—asbestosis, lung cancer, and mesothelioma—were fully understood.

Approximately 85% of the world's asbestos was produced from ophiolite complexes, most of which was the chrysotile variety; tremolite, actinolite, and anthophyllite asbestos accounting for only a few percent of the total. Asbestos minerals crystallize within tectonized ophiolites—along shear, fault, and dilation zones, and at contacts with intruded dikes and sills. Important chrysotile asbestos mines are found in the ophiolites of eastern Canada, the Russian Urals, California, northwest Italy, northern Greece, and Cyprus. A high incidence of mesothelioma, a cancer of the lung lining, is reported among residents of villages located within or near ophiolite complexes in Greece, Turkey, Cyprus, Corsica, and New Caledonia. These villagers were exposed to tremolite asbestos while processing stucco and whitewash for application to homes. Asbestos contamination in various geographic localities has generated concern about health risks and has prompted costly remedial actions, especially in the United Kingdom and the United States. A scientific basis for public policy is offered to address the utilization of asbestos-bearing rocks.

Keywords: mineral fibers, asbestos, chrysotile, tremolite, serpentines, serpentinite, lung cancer, mesothelioma, ophiolite.

INTRODUCTION

Ophiolite complexes, including the associated serpentinite belts, are found in many parts of the world. It was in these rocks that asbestos was first discovered and utilized as long as 5,000 years ago and from which ~85% of the world's asbestos was produced, most being chrysotile asbestos. This paper is intended to give the ophiolite specialist insight to the importance of ophiolites as a source of chrysotile, tremolite, actinolite, and anthophyllite asbestos by presenting their mineralogical descriptions, the nature of crystal growth of the asbestos minerals, their mode of occurrence within ophiolite complexes, and descriptions of some of the more important ophiolite-hosted asbestos deposits. We will discuss the origin of the Latin and English word "asbestos" from the writings of the ancient Greek and Roman philosophers; present a history, from ancient times to the present, of the discovery, production, and utilization of the various asbestos minerals; and

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*Mailing address, Ross: 1608 44th Street, NW, Washington, D.C. 20007, USA. E-mails: Ross—mrdrr@earthlink.net; Nolan—rnolan@gc.cuny.edu.

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present an early history of the development of an understanding of asbestos-related disease that took such a toll on asbestos workers' lives. Epidemiological studies are presented to show that asbestos workers who experienced uncontrolled asbestos exposures, such as miners, millers, and insulators, developed three serious diseases: asbestosis (scarring of the part of the lung where gas exchange takes place), lung cancer, and mesothelioma (cancer of the lining of the lung and abdominal cavity). From British medical pneumoconiosis studies of asbestos workers in the early part of the twentieth century to the recent epidemiological studies, there developed a great concern over the health effects of asbestos and as a result many countries have promulgated strict regulations for the use of asbestos (WHO, 1989). More recent bans on the mineral's use have been adopted or proposed (see Wilson et al., 2001). The Fifth Circuit Court of Appeals struck down the U.S. Environmental Protection Agency's (EPA) proposed ban on asbestos in 1991, citing the EPA's failure to pursue the least burdensome, most reasonable regulation required to protect the environment adequately (United States Court of Appeals, 1991).

In addition to chrysotile asbestos, tremolite and actinolite asbestos minerals are also found in ophiolites, but have been mined only in small quantities. As will be discussed, these two asbestos minerals present a much more serious health problem to miners and other workers than does chrysotile asbestos.

Six ophiolite localities in Turkey, Greece, Cyprus, Corsica, and New Caledonia are described, where the residents of nearby rural villages were exposed to tremolite asbestos through its use as ingredients for stucco (a fine plaster composed of cement mixed with asbestos added for strengthening) and whitewash (usually a mixture of water, asbestos, and calcium carbonate).

Examples will be presented of some of the asbestos mitigation efforts now being undertaken in the United States and Cyprus. In the discussion, we present the scientific basis for developing a public policy to address the health hazards when mining or construction activities occur in rocks that contain fibrous minerals.

ORIGINS OF THE WORD "ASBESTOS"

The various words used in antiquity to denote the asbestos minerals—including asbestos, asbestus, asbestinon, asbest, asbeste, asbeston, abeston, amiantos, amiantus, amianthus, amiant, and amiante—can be traced back to the writings of the ancient Greek philosophers and their use of two words—αμιαντος and ασβεστος. The Greek word αμιαντος (transliterated as "amiantos"), when used as a noun is synonymous with the English word asbestos, and when used as an adjective can mean pure or undefiled (G.E.L., 1940, p. 83). The Greek word ασβεστος (properly transliterated as "asvestos"—not "asbestos"), when used as a noun means lime, quicklime, or unslaked lime (CaO), and when used as an adjective, can mean inextinguishable, unquenchable, or not quenched (G.E.L., 1940, p. 255). Note, that quenching or slaking of calcium oxide with water produces calcium hydroxide. Latin translations of the Greek words for asbestos and quicklime have caused some confusion that is perhaps related to the difficulty of translating the complex noun and adjective declensions of Greek into Latin, an equally complex language, to the interchange of noun modifiers and nouns, and to the Greek versus Latin transliteration of the letter β.

The Greek physician, Pedanius Dioscorides of Cilicia (40–90 A.D.) reports of an "undefiled stone," αμιαντος λιθος—transliterated as "aminatos lithos," that occurs in Cyprus and resembles fissile alum that can be woven and is not consumed by fire (*Materia Medica*, 5, 138; see also G.E.L., 1940, p. 83 and O.E.D., 1933, p. 280). In modern Greek usage, the noun λιθος ("lithos") is omitted and replaced with αμιαντος ("amiantos"), synonymous with the Latin and English noun asbestos, the German and Russian noun asbest, the French nouns asbeste and amiante, and the Italian and Spanish nouns asbesto and amianto.

The ancient Greek writers (e.g., Dioscorides, *Materia Medica*, 5, 115; see also G.E.L., 1940, p. 255 and O.E.D., 1933, p. 480) used the noun ασβεστος ("asvestos") to mean quicklime; a meaning retained in modern Greek; however, Pliny the Elder (Caius Pliny Secundus, 23–79 A.D., *Natural History*, Book 19, paragraph 20; see also Rackham, 1961, p. 432–433), apparently misunderstanding the use of this word by the early Greek philosophers, replaced the Greek noun for quicklime (ασβεστος) with the dubious Greek word ασβεστινον (G.E.L., 1940, p. 255), which he interpreted to mean a non-combustible material. Pliny then transliterated ασβεστινον into the Latin noun "asbestinon," alluding to an incombustible linen, cleansed by fire, and used as shrouds for royalty during cremation. Pliny also refers to this incombustible linen as linum vivum—live linen. Pliny was undoubtedly referring to what we now know as asbestos cloth but reported that the material came from a plant that "grows in the deserts and sun-scorched regions of India" (Rackman, 1961, p. 433).

A computer search for the many variations of the word for asbestos that possibly may have been used in the 37 books of Pliny's *Natural History* (which is copied onto an Internet website; Thayer, 2002) revealed that Pliny, in addition to "asbestinon" (Book 19, 20), used the words "amiantus" (Book 36, 139; see also Bailey, 1932, p. 120–123, 256–257) and "asbestos" (Book 37, 146, Thayer, 2002). Pliny states that "amiantus" resembles alumen in appearance and is not destroyed by fire. The alumen of Pliny is probably not alum as we know it (potassium aluminum sulfate), but possibly an iron sulfate efflorescent produced by decomposition of pyrite (see Hoover and Hoover 1950, footnote 11, p. 572). In using the word "amiantus," Pliny may indeed be describing an asbestos mineral, but relating it to alumen because of similarity of certain physical properties.

In Book 37, 146, Pliny states that iron colored "asbestos" is found in the Arkadian mountains (located in the central Peloponnesus of Greece) perhaps suggesting that this fibrous material has a mineral origin. Here Pliny has taken the Greek word "asvestos" (quicklime) to mean something quite different—a fibrous mineral, now referred to as "asbestos" in both the Latin and English languages. It is not at all clear whether Pliny really understood the geological origin of asbestos, whereas ancient Greek writers, such as Strabo, Dioscorides, and Theophrastus, certainly did.

In summary, various words for asbestos have entered the vocabulary of Latin and other languages; the words amiantus, amianthus, amiant, amiante, and amianto were derived from the Greek word αμιαντος—"amiantos," whereas the words asbestos, asbestus, asbestinon, asbest, asbeste, asbeston, abeston, and asbesto were derived from the Greek word ασβεστος—"asvestos".

HISTORY OF ASBESTOS DISCOVERY, PRODUCTION, AND UTILIZATION

Early Beginnings

While the general use of asbestos in international commerce dates only to the late nineteenth century, its utility in human culture goes back at least 4,500 years. Archeological studies (Europaeus-Äyräpää, 1930) show that inhabitants of the Lake Juojärvi region of East Finland knew how to strengthen earthenware pots and cooking utensils with an asbestos mineral, later identified as anthophyllite (anthophyllite asbestos was mined commercially in East Finland between 1918 and 1975). According to Huuskonen (1980; see also Europaeus-Äyräpää, 1930 and 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. One of the most important uses of asbestos in the twentieth century—to strengthen materials—was used for this purpose several thousand years ago.

There is also evidence that asbestos was discovered and utilized in Cyprus during classical times, perhaps as long as 5,000 years ago, for manufacture of cremation cloths, lamp wicks, hats, and shoes (Dioscorides, *Materia Medica*, 5, 138). Bowles (1955, p. 9) suggests a location for the ancient asbestos deposits, and states that Cyprus was a well known source of asbestos in ancient times and that "although it is difficult to determine, from early references the exact location of the ancient deposit, probably it was southeast of Mount Troodos in a village known as Amianto the identity of which is lost." Evans (1906, p. 145) states that sixteenth-century travelers referred to the existence of abandoned asbestos mines near the village of Paleandros or Pelendria. Pelendria (now Pelendri) is situated within the Troodos ophiolite complex and ~6 km southeast of the Mount Troodos chrysotile asbestos mine; however, Dr. George Constantinou, former head of the Cyprus Geological Survey Department, suggests that asbestos was mined in ancient times near the towns of Vavla, Vasa, and Apsiou, 25 km southeast of Mount Troodos. These towns are located within the Akapnov Forest, a large area of ophiolite terrane within the Arakapas (transform) Sequence. We suggest that the ancient asbestos deposits were located within the Akapnov Forest area; the deposit near Pelendri may have been developed much later and prior to opening of the nearby Mount Troodos chrysotile asbestos mine in 1904.

The descriptions of asbestos use in Greece clearly goes back more than 2000 years. Herodotus (ca. 484–425 B.C.) clearly documented the use of asbestos for lamp wicks in the early Greek civilization. The Greek philosopher Theophrastus (ca. 372–287 B.C.), one of Aristotle's students, was perhaps one of the first to carefully describe the mineral we now call asbestos as "a stone, in its external appearance somewhat resembling wood, on which, if oil is poured, it burns; but when the oil is burnt away, the burning of the stone ceases, as if it in itself not liable to such accidents" (Hoover and Hoover, 1950, p. 440, footnote 5). Plutarch (ca. 46–120 A.D.) recorded that the vestal virgins used "perpetual" lamps to serve Rome's sacred fire (the fabrication of asbestos lamp wicks, such as described by Herodotus and Plutarch, probably was an important cottage industry in Greek and Roman times). Pliny, as discussed before (Book 19, 20), refers to tablecloths, lamp wicks, and a rare and costly asbestos cloth—lithium vivum—the funeral dress of kings. Pliny's reference to iron colored asbestos occurring in the Arkadian mountains (Book 37, 146) is supported by the town history of Kandyla, Province of Arkadia, central Peloponnesus, Greece. In a translation from the original ancient Greek, it is reported that early in the first millennium there was a merger of three towns into one—Kandyla. Further, it is stated that after the merger "the inhabitants began to construct homes that were solid, with the use of such materials as stone and asbestos" (Deligiannis, 2002, p. 1). As will be mentioned latter, villagers in the rural areas of Greece, as well as in other countries, commonly applied asbestos-bearing stucco and whitewash to their homes.

The Greek geographer, Strabo (64 B.C.–21 A.D.), in *Geographia*, Book 10, (see also Bailey, 1932, p. 256) referred to a "Karystian stone" obtained from quarries near Karystos (Karistos), a town on the southern tip of the Greek island of Euboea (Evvia). Hoover and Hoover (1950, p. 440, footnote 5) quoting from Strabo (Book 10, 1): "at Carystus (Karystos) there is found in the earth a stone, which is combed like wool, and woven, so that napkins are made of this substance, which when soiled, are thrown into the fire and cleaned, as in the washing of linen." Examination of geologic maps of Evvia shows extensive outcrops of ophiolitic rocks in the north-central region of the island and one smaller outcrop ~30 km north of Karystos (Rassios and Smith, 2000, fig. 2; Geological Map of Greece, Division of Geology and Economic Geology, Athens, 1983). Thus, this ancient source of asbestos known to the ancients as "Karystian stone," may have been quarried within ophiolite terrane.

There are also numerous references (see Bowles, 1955. p. 8–10) to the use of asbestos in post-Roman times and before the start of the modern asbestos industry in the late part of the nineteenth century. The origin of asbestos remained a subject of fanciful speculations into the Middle Ages, when alchemists made claims that asbestos was the hair of a type of fire-resistant salamander (Alleman and Mossman, 1997). Since at least the early part of the sixteenth century, the image of the salamander has been symbolic for asbestos. Probably the most famous anecdote is that of Charlemagne (or, according to some writers, Charles V) astonishing his guests by cleansing a tablecloth by throwing it into a fire. Marco Polo, in his travels through Siberia during the thirteenth century, mentions the "amianthus" cloth, which resisted the action of fire.

As early as 1720, chrysotile asbestos was commercially mined in the Urals Region of Russia along the Tagyl River in the Middle Urals. The silky mineral fibers were woven into cloth to fabricate aprons, gloves, and caps for the high-temperature shops of the eighteenth-century metallurgical plants that were common in the Urals. In 1722, a sample of the asbestos cloth was presented to Peter the Great (Kashansky, 1999).

Start of the Modern Industry

In the 1860s and 1870s, the market for asbestos products rapidly expanded, probably for three reasons: the need for insulation for the new steam technology, the formation of an international consortium of Italian and English entrepreneurs, and the reopening of the asbestos deposits in northern Italy and simultaneous development of the vast chrysotile resources in Quebec, Canada. By 1890, the modern asbestos industry was full blown, with hundreds of applications being introduced (Jones, 1890; Alleman and Mossman, 1997).

Chrysotile and tremolite asbestos deposits in the Susa, Lanzo, Aosta, and Val Malenco areas of the Italian Alps were first exploited in Roman times, but it was not until the early 1800s when manufacture of asbestos threads, fabrics, and paper was perfected, that the alpine deposits became economically important. Between 1860 and 1875, several new Italian companies formed to advance the technology of fabrication of asbestos into spun products, rope packings, and heat-insulating board. Exhibits by these companies at the Paris Universal Exposition in 1878 helped to bring these asbestos products to international attention. (Ross, 1981; Bowles, 1955).

Marcuse (1930) describes the first discovery of asbestos in the Province of Quebec, Canada by the early French settlers who referred to the local asbestos (now known to be chrysotile) as “Pierre á Coton” (the cotton stone). Bowles (1955) reports that the first small deposit of asbestos was discovered near St. Joseph, Quebec in 1860 and samples of the mineral were exhibited in London in 1862; however, the first deposit capable of major development was discovered near Danville, Quebec, in 1877. Active mining began in 1878, when 50 tons of fiber was produced. By 1885, seven asbestos mines, centered around the town of Thetford Mines, were in production.

Asbestos was discovered in the Ural Mountains near the city of Ekaterinburg in the early part of the eighteenth century and the fiber was used sporadically in textile production. Systematic development of the Ural deposits, however, did not began until the huge Bazhenovskoye deposit of chrysotile asbestos was discovered near Asbest City in 1884. Commercial mining of this deposit began in 1886, and by 1889 24,000 tons of chrysotile asbestos had been produced. Since 1918, the mines and mills have been operated by the Uralasbest Company (Shcherbakov et al., 2001).

The occurrence of “crocidolite” asbestos was discovered in 1812 in the Profret area, Northern Cape Province, South Africa, but it was not until 1893 that asbestos production began near the town of Koegas and in 1926 near the Pomfret area (Beukes and Dreyer, 1986). “Amosite” asbestos was discovered near the town of Penge, Transvaal Province, South Africa, in 1907, and commercial production began in 1916 (Bowles, 1955).

Asbestos Production

From the time of the first recorded use of asbestos by Stone Age man to 1900, total world production was probably between 200,000 and 300,000 metric tons. Of this, 150,000 tons were produced in Quebec, Canada (Ross, 1981). After World War I, use of asbestos greatly increased; total world production of all forms of asbestos between 1931 and 1999 was ~166 million metric tons (Ross and Virta, 2001), of which 90 to 95% was the chrysotile variety. A large percentage of the total chrysotile production was from ophiolite complexes. Approximately 3 million metric tons each of “amosite” and “crocidolite” asbestos have thus far been mined worldwide, and ~350,000 metric tons of anthophyllite asbestos was mined in east Finland (Huuskonen et al., 1980). Commercial production of tremolite and actinolite asbestos has been small and sporadic. Russia is the leading producer of asbestos, followed (in decreasing amount of production) by China, Canada, Brazil, Zimbabwe, and Kazakhstan. At present, the only producing asbestos mine in the United States is located within the New Idria serpentinite, located at the south end of the Diablo Range, California.

THE ASBESTOS MINERALS

Chrysotile Asbestos

Chrysotile asbestos, the only fibrous member of the serpentine mineral group, has the ideal chemical formula $Mg_3Si_2O_5(OH)_4$. Small amounts of aluminum, iron, manganese, calcium, potassium, and sodium may enter the crystal structure of this mineral. The chrysotile fibers consist of long hollow “rolled up” tubes and each fibril is ~25 nanometers in diameter, with lengths varying from well under one micrometer for an individual fibril to well over 10 cm for fiber bundles (Fig. 1). Chrysotile is identified by a combination of optical properties, quantitative chemical analysis, polyfilamentous bundles, size, hollow tube morphology, and a characteristic powder x-ray diffraction or selected area electron diffraction pattern (Langer and Nolan, 1994; Wicks, 1999). Chrysotile asbestos is by far the most common asbestos mineral, generally occurring at trace levels in most serpentinites, whereas the commercial deposits contain several volume percent of this mineral.

Amphibole Asbestos

The three main forms of amphibole asbestos found in ophiolite complexes are: (1) anthophyllite asbestos, ideally $(Mg,Fe^{2+})_7Si_8O_{22}(OH)_2$, where 0 to 50 atom percent of Mg can be replaced by Fe^{2+}; (2) tremolite asbestos, ideally $Ca_2(Mg,Fe^{2+})_5Si_8O_{22}(OH)_2$,

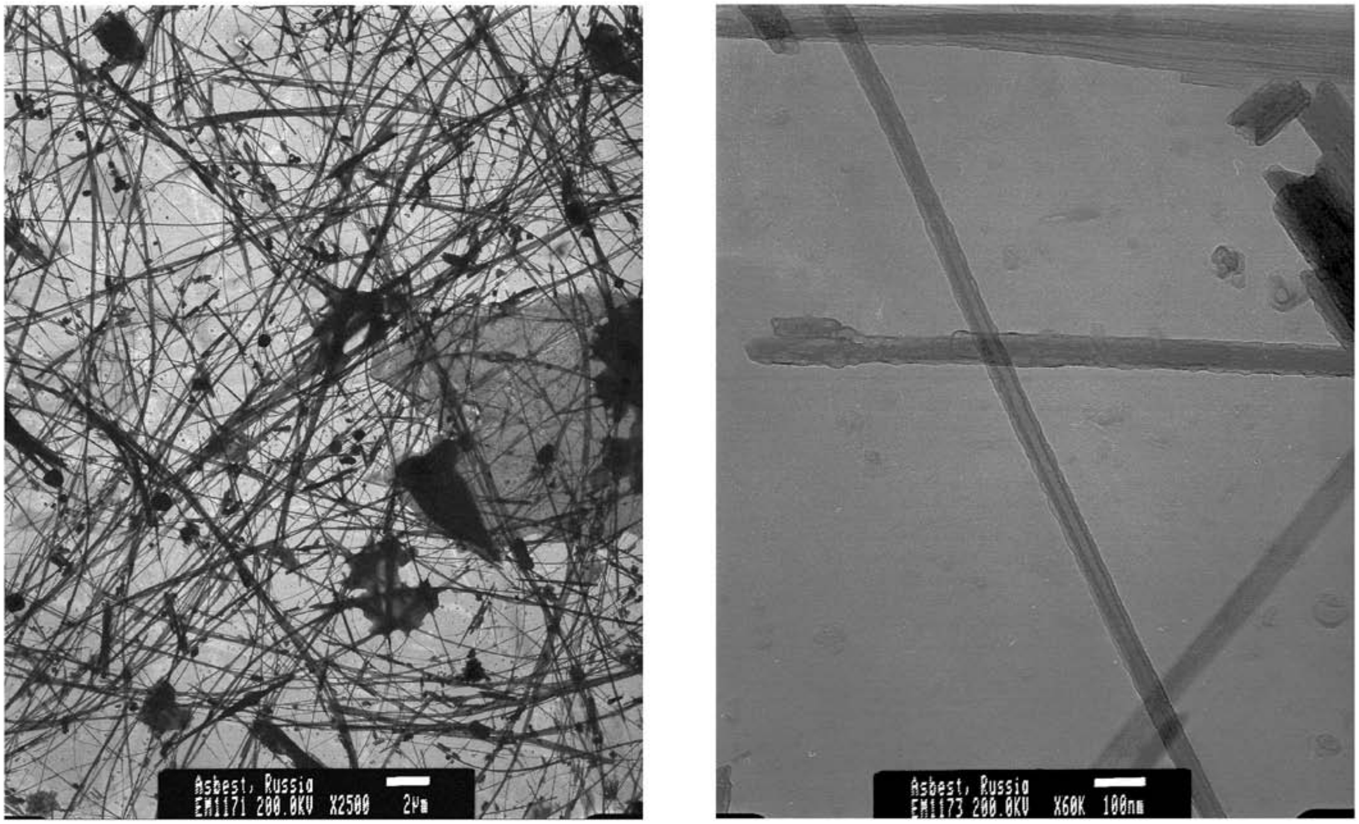

Figure 1. Transmission electron photomicrograph of chrysotile asbestos displaying polyfilamentous bundles of fibers and individual fibril having a central capillary associated with the hollow tube structure.

where 0 to 10 atom percent of Mg can be replaced by Fe^{2+}; and (3) actinolite asbestos, ideally $Ca_2(Fe^{2+},Mg)_5Si_8O_{22}(OH)_2$, where 10 to 50 atom percent of Mg can be replaced by Fe^{2+} (Leake et al., 1997). The amphibole asbestos minerals are characterized by their chemical composition, distinctive diffraction patterns, generally long straight fiber morphology, and transparency to electrons when viewed by transmission electron microscopy. Fibers typically vary in width from 0.1 to >1 micrometer and in length from a few micrometers to several centimeters.

Anthophyllite asbestos was mined mostly within an ophiolite complex located in the Paakkila (Tuusniemi) area of East Finland. With the close of the Finnish mines in 1975, there is now very little anthophyllite mined anywhere in the world. Small amounts of anthophyllite were mined earlier in this century within the serpentinite belt of the eastern United States, particularly in the states of Georgia, Maryland, and North Carolina. Minor amounts of tremolite asbestos and actinolite asbestos have been mined in various serpentinite belts, but were (with a few exceptions) of little commercial importance and mined mostly for local uses. Tremolite and actinolite asbestos is still possibly being mined to a very limited extent in ophiolites of Greece and Turkey, and perhaps in ophiolites of Cyprus and Iran. The asbestos minerals in the tremolite-actinolite series are associated with environmental mesotheliomas in several countries and are much more hazardous than chrysotile and anthophyllite asbestos. Thus, it would be useful for geologists to particularly note their presence and any mining activity during field investigations.

The two other commercial asbestos minerals, which do not occur in ophiolite complexes, have been important in commerce. These are: (1) grunerite asbestos, $(Fe^{2+},Mg)_7Si_8O_{22}(OH)_2$, usually referred to colloquially as “amosite” (from the acronym AMOS, representing Asbestos Mines of South Africa), which was mined only in metamorphosed banded iron formations of the Cape Province of South Africa; and (2) riebeckite asbestos, $Na_2(Fe^{2+},Mg)_3Fe_2^{3+}Si_8O_{22}(OH)_2$, usually referred to colloquially as “crocidolite,” which was mined in four localities—in the banded iron formations of the Transvaal and Cape Provinces of South Africa, in the iron formations of the Hammersley Range of Western Australia, and in the Cochabamba area of Bolivia. The geologic occurrence and mineralogy of the asbestos minerals are discussed in detail in Ross (1981, 1984), Skinner et al. (1988), and Veblen and Wylie (1993).

It should be noted that five of the six minerals designated as asbestos (tremolite, actinolite, anthophyllite, grunerite, and riebeckite asbestos) can also occur in a non-fibrous form. It is important to use the mineralogical definition of asbestos for identification. Historically, non-asbestos fibers (for which there is no evidence of an asbestos health hazard) have occasionally been misidentified as asbestos (Langer et al., 1991; Langer, 2001).

Crystal Growth of Asbestos Fibers

Most asbestos appears to crystallize under very special conditions that occur within rock formations that are undergoing intense deformation characterized by folding, faulting, shearing, and dilation. Such deformations are often accompanied by the intrusion of magmatic fluids forming dikes and sills. The fibers crystallize in high strain environments, such as within folds, shear planes, faults, dilation cavities, and at intrusion boundaries. Ophiolite complexes are highly tectonized rocks containing many of these deformation attributes, thus they present conditions ideal for fiber formation.

Slip-fibers are formed within the fault and shear zones, the fibers crystallizing or recrystallizing from solutions that move within the two rock faces that compose the shear or *slip* plane—thus the term *slip-fiber* (Fig. 2). We observed this type of fiber formation in samples collected from a shear zone within a metamorphosed iron formation in northeastern Minnesota. There non-fibrous ferroactinolite had come into contact with low temperature acidic solutions that were moving through an active shear zone, causing the amphibole to recrystallize into a fibrous form having the fiber axis lying parallel to the shear and flow plane. Nolan et al. (1999) report on the occurrence of grunerite asbestos ("amosite") in a similar iron formation in Michigan. They state that "grunerite asbestos is developed within quartz-ankerite-stilpnomelane veins and along their contacts with the host rock and sills. The veins are deformed and exhibit signs of shearing, brecciation, faulting, and folding" (p. 3413).

Cross-fibers occur within cracks formed when the rock undergoes dilation due to tectonic stress, a process in which parallel cracks and fissures form open spaces in the rock. The process of folding in layered rocks can also produce openings or dilation cavities between adjacent layers. Asbestos crystallizes from a fluid phase, the fibers nucleating on a wall of the crack or cavity and growing toward the opposite wall—thus the term *cross-fibers*. Examples of cross-fiber growth within folds occur in the "crocidolite" and "amosite" deposits of South Africa and the "crocidolite" deposits of Western Australia. There, the fibers crystallized only where the Precambrian banded iron formations were folded into monoclines, inducing splitting and dilation cavities between mesobands (Dreyer and Robinson, 1981; Trendall and Blockley, 1970).

ASBESTOS AND DISEASE

Early History of Asbestos-Related Disease

While great advances were being made to advance the technology of asbestos mining and milling and invention of new uses for asbestos through product development, giving tangible benefits to society, asbestos workers were dying of asbestos-related diseases from exposure to asbestos dusts.

The ancient world recognized the remarkable properties of asbestos and wrote about the "magic mineral" and its ability to resist fire; however, the health effects associated with the inhalation of asbestos fiber were not known to any of the ancient writ-

Figure 2. Large sheets of nemalite (fibrous brucite-chrysotile), occurring as a slip-fiber in Mine Jeffrey, Quebec, Canada. The Canadian coin for scale is 2.8 cm in diameter.

ers, including Pliny and Strabo (Browne and Murray, 1990). For example, some cite Pliny the Elder (*Natural History*, Book 33, 122) as referring to the use of respiratory protection against asbestos; however, Browne and Murray (1990, p. 445) note that in this instance the workers were exposed to cinnabar (mercury sulfide), not asbestos. The earliest reports of asbestos-related disease were from France and the United Kingdom in 1906 (Murray, 1990). These early reports on asbestos-related disease describe pulmonary fibrosis associated with exposure to chrysotile asbestos. In 1927, the term asbestosis was used for the first time in English to describe this disease and the coated asbestos fiber present in the lung were referred to as "asbestos bodies" (Cooke, 1927).

These early cases of asbestosis generally occurred in individuals who also suffered from the disease tuberculosis, which complicated the clinical presentation of the new disease—asbestosis. It was not long before the first case of asbestosis without associated tuberculosis was reported in Glasgow by Dr. H.E. Seiler, who attributed the pulmonary fibrosis to asbestos exposure (Seiler, 1928). Once the clinical existence and features of asbestosis were known, its occurrence among asbestos workers could be detected.

In 1934, Drs. W.B. Wood and S.R. Gloyne reported finding two lung cancer cases among a series of 100 cases of asbestosis (Wood and Gloyne, 1934). The initial observations related lung cancer to asbestosis rather than asbestos. In the 1930s, lung cancer was still a rare disease because it was not until after World War I that cigarette smoking, the major cause of lung cancer, became a common habit. The relationship between cigarette smoking and lung cancer would not become commonly known until the 1950s (Doll and Hill, 1950).

In the United States, lung cancer was also reported among individuals with asbestosis (Lynch and Smith, 1935) and case reports of lung cancer among individuals would continue to appear for decades. In the United Kingdom, Doll (1955) reported on a cohort of 113 men with at least 20 years of occupational exposure to chrysotile asbestos. Eleven lung cancers occurred in this cohort where <1 case of lung cancer would have been expected, based on the rate of this disease among males in the general population. All of the lung cancer cases showed histological evidence of asbestosis. These reports provided strong evidence that individuals with asbestosis were at increased risk of lung cancer, but no mention is made about smoking in general or the smoking habits of the workers.

Diseases Related to Exposure to the Various Asbestos Minerals

Three principal diseases are related to exposure to the asbestos minerals. (1) *Asbestosis* is a non-malignant diffuse interstitial fibrosis of the lung tissue. High asbestos exposure leads to scarring of the lung, causing it to become stiff, resulting in a restriction in pulmonary function and reduction in the lung's ability to exchange carbon dioxide for oxygen. (2) *Lung cancers* related to asbestos exposure are bronchogenic carcinomas, which include squamous carcinomas, small- or oat-cell carcinoma, and adenocarcinomas. Cancers that arise in other parts of the lung, such as alveolar carcinomas and sarcomas, are rare and are not known to be caused by asbestos. (3) *Mesothelioma* is a cancer of the pleura, pericardium, and peritoneal membranes, which surround the lung, heart, and abdominal cavities, respectively. The pleural mesothelial cells occur almost as a monolayer surrounding the outside of the lung and the inside of the chest wall. Mesothelioma is mainly restricted to those exposed to the amphibole asbestos dusts—"crocidolite," tremolite, and grunerite.

Those exposed to asbestos sometimes develop pleural plaques on the covering epithelium of the lung. Plaques are largely acellular bundles of collagen, sometimes calcified, and are detected on chest X-ray films. Although benign, they may indicate future development of asbestos diseases. For complete reviews of asbestos-related diseases, see Dement et al. (1986), Skinner et al. (1988), and Henderson et al. (1992).

For regulatory purposes, all six asbestos minerals have often been assumed to be equally harmful to human health (until proven otherwise), but recently this assumption has been questioned (see Wilson and Crouch, 2001, p. 231–232). Examination of the many epidemiological studies, where the effects of the individual asbestos minerals can be evaluated separately, provides convincing evidence that "crocidolite" and tremolite asbestos are clearly more dangerous than chrysotile asbestos (McDonald and McDonald, 1996; Hodgson and Darnton, 2000; Nolan et al., 2001). "Crocidolite" (also referred to as "blue asbestos") in particular is associated with a high incidence of mesothelioma. Wagner and co-workers (Wagner et al., 1960; Wagner, 1991) first discovered that the pleural form of this very rare disease could be caused by "crocidolite" dust during their study of the occurrence of 33 mesothelioma cases among individuals exposed to "crocidolite" in the northwestern Cape Province of South Africa. Mesothelioma occurs so rarely that prior to discovery of the many mesothelioma cases occurring among the Cape Province miners, many pathologists doubted the existence of the disease (McDonald and McDonald, 1996). Dr. J. Christopher Wagner (Wagner, 1991) not only proved that "crocidolite" is an etiological factor in mesothelioma, but also established mesothelioma as a respiratory disease, thereby defining one of the most important thoracic tumors identified in the twentieth century.

Conventional epidemiological studies could not address the health effects of some of the other fibrous minerals of less commercial importance because a statistically significant cohort of exposed individuals could not be assembled; however, prevalence studies of certain populations with a high incidence of mesothelioma began appearing in the medical literature, the first being a study of the "crocidolite"-exposed individuals in South Africa. The second significant study was of residents of the village of Karain, located in the Cappadocia region of Turkey. In Karain, from 1970 to 1978 there were 76 deaths, of which 50 were due to pleural mesothelioma (Baris et al., 1979; Saracci et al., 1982).

Background mesothelioma incidence in the general population is one case among 10,000 deaths, making the incidence in Karain more than 6,000-fold above background. No asbestos exposed cohort has experienced an incidence of mesothelioma as high as those living in Karain. The fibrous zeolite mineral erionite, $NaK_2MgCa_{1.5}(Al_8Si_{28}O_{72})\cdot 28H_2O$, is found in the local ash-flow tuffs, soils, and air samples and is implicated in the mesothelioma epidemic (Baris, 1991). The particular erionite samples from the Karain area contain extremely thin and long fibers, comparable in size and shape to the finest amphibole asbestos fibers. Experimental animal studies, in which rats were exposed to erionite by inhalation, indicate erionite has a much greater potency to induce mesothelioma than does "crocidolite" asbestos (Wagner et al., 1985). In addition to erionite, tremolite asbestos has been associated with environmental mesothelioma in Turkey and cases have been reported among Turkish immigrants (Dumortier et al., 2001).

Studies of Workers Occupationally Exposed to Asbestos

Three commercially important forms of asbestos, chrysotile, "amosite," and "crocidolite," were used extensively throughout the industrialized world from the late 1800s until recently (Alleman and Mossman, 1997). Ross (1984) and Ross and Virta (2001) provide historical data on asbestos use in the United States in terms of the import tonnages and the commercial applications of each of the asbestos fiber types. A large number of miners and trades workers were exposed to one or more of these three types of asbestos, thus statistically significant epidemiological studies could be made of various cohorts of workers.

Anthophyllite use was restricted mostly to Finland where epidemiological studies of Finnish asbestos miners were undertaken (Meurman et al., 1974). Asbestosis and lung cancer risk increased with the miner's exposure to anthophyllite; no mesotheliomas were reported. Evidence for anthophyllite asbestos-related mesothelioma has been rather limited. Timbrell et al. (1971) hypothesized, on the basis of anthophyllite fiber having a diameter greater than "amosite" and much greater than "crocidolite," that exposure to anthophyllite would rarely if ever produce mesotheliomas (see Timbrell, 1989, for further discussion). More recently, lung content studies reported finding anthophyllite asbestos within the functional tissue of the lung (the parenchyma) of individuals with mesothelioma. Generally, these individuals were not anthophyllite miners and the analysis revealed the presence of other asbestos fiber types more commonly associated with mesothelioma (Tuomi et al., 1989). In 1994, four mesothelioma cases were reported among anthophyllite asbestos miners (Karjalainen et al., 1994). All four had exposure sufficient to induce asbestosis, which is consistent with the evidence that anthophyllite asbestos is weakly mesotheliomagenic. This is the most persuasive evidence that uncontrolled exposure to anthophyllite asbestos may result in mesothelioma, particularly if the fibers are very thin. A mesothelioma case has recently been reported in a 38-year-old male without asbestosis from neighborhood exposure (Rom et al., 2001). We remain skeptical about etiology in this case report.

Little tremolite and actinolite asbestos was used in commerce; thus, no large cohort could be assembled for the usual epidemiological analysis. As will be discussed below, however, mesothelioma cases have appeared in certain small groups of workers mining and processing tremolite asbestos for building materials.

The Asbestos Trades Workers

A very significant increased incidence, in relation to the general male population, of lung cancer, mesothelioma, and asbestosis is found in men who were employed in the "asbestos trades," e.g., work involving the asbestos insulation of pipes, steam boilers, and buildings and in the production of asbestos textiles, roofing materials, friction materials, wall board, etc. These trades workers generally handled all three common forms of commercial asbestos (chrysotile, "amosite," and "crocidolite") during their working careers. Ross (1984, p. 307) lists the mortality data for 13 epidemiological studies of asbestos trades workers. These 13 studies demonstrate that in most asbestos trades worker cohorts, there was a large excess death due to lung cancer, mesothelioma, and asbestosis. Lung cancer mortality, however, was much greater for smokers than for nonsmokers.

The asbestos miners and millers. Unlike the trades workers, the men working in the mining and milling of asbestos were generally exposed to only one type of asbestos mineral; a few exceptions occur in the mining regions of South Africa, where some workers were employed in "crocidolite," "amosite," and chrysotile mines. Epidemiological studies of miners and millers exposed to only one type of asbestos mineral permit one to ascertain the human health effects of the different types of asbestos. Ross (1984, p. 309) gives mortality data for the five major epidemiological studies of asbestos miners and millers; one is a cohort of anthophyllite asbestos miners, one is a cohort of "crocidolite" miners, and three are cohorts of chrysotile miners. The mortality patterns noted on comparing the trades and mines cohorts makes it clear that there are very significant differences in the human health effects of the four different asbestos minerals, with "crocidolite" being the most dangerous, followed in decreasing order of pathogenicity by "amosite," and chrysotile (for a recent review, see Hodgson and Darnton, 2000). Mesothelioma incidence is particularly high in those exposed to "crocidolite," moderately high to those exposed to "amosite," and very low in those exposed to only to anthophyllite or chrysotile asbestos.

Moderate-Level Exposures to Mostly Chrysotile Asbestos

Several epidemiological studies of asbestos trades workers show no significant increased risk of asbestos-related disease among individuals exposed to chrysotile asbestos dusts, but having little or no exposure to amphibole asbestos dusts. Their exposure levels, however, were much higher than those observed in schools and in other non-occupational settings (Wilson et al., 1994; Nolan and Langer, 2001). Examples of such epidemiological studies include: (1) Cardiff, Wales, asbestos cement workers (Thomas et al., 1982); (2) New Orleans, Louisiana, asbestos cement workers (Weill et al., 1979); (3) Swedish asbestos cement workers (Ohlson and Hogstedt, 1985); (4) English asbestos cement factory workers (Gardner et al., 1986); and (5) British friction product workers (Newhouse and Sullivan, 1989).

The health experience of the five above-mentioned cohorts is in great contrast to many other asbestos workers who worked under the historically high exposures, such as occurred in asbestos textile manufacturing, during installation and removal of asbestos in heating and electrical conduits, in poorly ventilated asbestos factories, and in workplaces and mines where there was exposure to large quantities of "crocidolite" and "amosite" asbestos dust (Ross, 1981, table 4). Worker cohorts engaged in such activities were often exposed to dust levels of hundreds of fibers per ml (Gibbs and DuToit, 1973; Doll and Peto, 1985).

Studies of Those Who Had a Non-Occupational Exposure to Chrysotile Asbestos

Mines within the towns of Thetford Mines and Asbestos, located in the province of Quebec, Canada, have produced over 40 million metric tons of chrysotile asbestos since first opening in 1878. Many mines have closed, but two large-capacity mines are still producing asbestos. These two towns have a combined population of 30,000, and a large number of the male residents work, or have worked, in the asbestos mines and mills. Most of the asbestos workers are male; very few are female. Historically, the ambient asbestos exposures were high in these towns and residents were continually exposed to asbestos dust from the nearby mines, mills, and mine waste dumps. Camus et al. (1998) give estimates of the number of ambient asbestos fibers (those longer than 5 micrometers) per milliliter (f/ml) of air in the two asbestos towns for the period 1900–1989. They state that average levels exceeded 1 f/ml during World War II and into the early 1950s. Thus, ambient chrysotile asbestos dust levels in these Quebec towns prior to the introduction of modern dust control technology in the 1970s were ~230 to 23,000 times the average levels found in schools with asbestos insulation (Ross, 1995, p. 186).

A mortality study was made by Siemiatycki (1982) of 1130 deceased women who had lived in Thetford Mines and Asbestos but did not work in the asbestos industries. This study shows that the health of these women was unaffected by these very high non-occupational 24-hour-a-day lifetime exposure to asbestos dust. The standard mortality ratio (SMR = observed deaths/expected deaths) for all cancer in these women is 0.91, for lung cancer is 1.07, for digestive cancer is 1.06, and for non-malignant respiratory disease is 0.58. None of these SMRs is statistically different from the control cohort composed of unexposed women of similar socioeconomic background living outside the asbestos mining townships (SMRs >1.2 might imply a statistically significant health risk). A previous study by Graham (1981) also showed no excess cancer among the female residents of these Quebec mining towns (also see Ross, 1984, p. 82–85). More recently, Camus et al. (1998) reported similar results in an update for lung cancer among this same population of women with non-occupational exposure to chrysotile asbestos in the Quebec chrysotile mining towns. Their study indicates that the U.S. Environmental Protection Agency overestimates the potency of chrysotile asbestos to increase lung cancer risk by a factor of at least 10.

A major breakthrough in bringing a new understanding of the relative health risks of asbestos to a scientific, political, and public audience came from the work of Mossman et al. (1990). Their paper was published in *Science* at the time when billions of dollars where being spent to remove asbestos from schoolrooms and other buildings in the United States. These authors stated: "clearly the asbestos panic in the U.S. must be curtailed." Their very low risk estimates to children attending classes in schools with asbestos-containing material were reviewed in detail by HEI.AR (1991) and Wilson et al. (1994). Data given in these references show that the average concentration of asbestos measured in 219 American schools is 0.00022 f/ml. Using this average fiber concentration and the most pessimistic methods (or worst case scenario) for calculating risk, the risk for residing in the classroom six hours a day, five days a week for 14 years is one excess cancer death per million lifetimes (Ross, 1995, table 1).

SOME OF THE IMPORTANT OCCURRENCES OF ASBESTOS IN OPHIOLITE COMPLEXES AND ASSOCIATED SERPENTINITES

In this review, we use a broad definition of the term *ophiolite* to include those rocks that at least in part are pieces of oceanic crust that have been obducted onto the edges of continental plates. The idealized ophiolite, from the base upward, includes: (1) layered cumulates or mantle sequence comprising tectonized dunites, lherzolites, and harzburgites; (2) gabbros; (3) sheeted diabase dikes; (4) pillow basalts; and (5) various marine sediments. The Troodos ophiolite of Cyprus (Robinson and Malpas, 1990) and the Semail ophiolite of Oman (Vetter and Stakes, 1990) are two of the best examples of places where complete or nearly complete sequences of these five rock types are exposed; however, not all of these rock types can be observed in outcrop in many of the ophiolite occurrences, including some of the important serpentinite belts of the world. O'Hanley (1996) gives a very comprehensive review of serpentine mineralogy and the petrology and geology of serpentinites.

Not included in this review are the chrysotile-bearing serpentinites of various greenstone terranes, for example, the Abitibi greenstone belt of Ontario, Canada, and the Barberton greenstone belt of South Africa, because characteristic ophiolite assemblages are not observed (O'Hanley, 1996, p. 217). Also not included in this discussion are the carbonate-hosted chrysotile deposits, such as those found in the Barberton-Caroline District and near Kanye, South Africa; in the Laiyuan district, Hepeh Province, China; and in Gila County, Arizona, USA.

Anthophyllite Asbestos Deposit in Finland

Significant commercial production of anthophyllite asbestos has occurred only in the north Karelian mountains of eastern

Finland. Here, several serpentinized ultramafic pods or lenses, which were originally dunite or enstatite-bearing peridotites, were exploited. These serpentinized masses, forming part of the Outokumpu ophiolite complex, are thought to have been a part of much larger slabs of oceanic material that during the Karelian mountain-building episode, broke up into smaller volumes and were emplaced into the Karelidic schist belt. Late Karelian granites were injected into the schist belts, and where these are in contact with the serpentinized peridotites, commercial quality anthophyllite was developed (Aurola, 1954; Simonen, 1980). The anthophyllite-bearing ultramafic pods typically contain relict olivine surrounded by serpentine aggregates and bundles of anthophyllite needles. Sites of major mining of anthophyllite asbestos were on the northern shore of Lake Juojärvi and at East Savo and Maljassalmi. Between 1918 and 1975, 350,000 metric tons of asbestos were produced (Huuskonen et al., 1980). The mines closed after 1975. Small quantities of anthophyllite asbestos were mined in the other parts of the world.

Major Chrysotile Asbestos Deposits in Ophiolite Complexes and Associated Serpentinites

Southern Quebec, Canada, and Northern Vermont, USA

The important North American chrysotile asbestos deposits are located in the towns of Asbestos and Thetford Mines, Quebec, Canada, and in the town of Eden Mills, Vermont, USA. These deposits are in the northern part of the Appalachian ultramafic belt, which extends intermittently from northwestern Newfoundland to the state of Alabama, USA. The Canadian and United States deposits are found in a narrow belt of Ordovician ophiolites, which have been extensively dismembered and sheared. In the asbestos mining area of Quebec, the ophiolite sequence consists of an amphibolite sole and overlying harzburgite, dunite, pyroxenite, gabbro, basalt, and pelagic sedimentary rocks. Both the harzburgites and dunites were serpentinized during emplacement of the ophiolite (Williams-Jones et al., 2001). The ophiolite dismemberment was accompanied by extensive shearing and the emplacement of numerous felsic dikes. Chrysotile asbestos probably formed in late-stage fractures during the stress environment of tectonic transport and emplacement of the serpentinite. Williams-Jones et al. (2001) note that minor amounts of amphibole occurring in the ore bodies are found mainly adjacent to the felsic dikes, but are effectively absent from the chrysotile-bearing serpentinite. They also observed: (1) narrow selvages of tremolite around the felsic dikes in the serpentinite, (2) tremolite asbestos as narrow shear and fracture-fillings in pyroxenite, and (3) actinolite asbestos as disseminations and fracture fillings in albitized felsic dikes and in slate proximal to serpentinite. A similar occurrence of tremolite asbestos was observed by one of us (Ross) in a vermiculite deposit in southern Virginia, USA. Here, small amounts of tremolite asbestos form thin slip-fiber coatings on the contact surfaces between the intruded felsic dikes and the altered amphibolite host rock. The contact surfaces have been sheared.

There are now only two active asbestos mines in southern Quebec: Mine Jeffrey, in the town of Asbestos, and Black Lake Mine, near the town of Thetford Mines. Mine Jeffrey is the largest Canadian producer, having an estimated yearly milling capacity of >250,000 metric tons. The Mine Jeffrey pit, the largest asbestos pit in the western hemisphere, is >2 km in diameter and is ~350 m deep (Fig. 3). Geologically, the asbestos deposit at Eden Mills, Vermont, is very similar to deposits in Canada. The Vermont mine is now closed, but at one time processed a large amount of slip fiber chrysotile asbestos, which was much desired for brake linings.

Coalinga, California, USA

The New Idria serpentinite (Fig. 4), which crops out within a mountainous 114 km^2 area 26 km northwest of Coalinga, California, forms the core of a large antiform between the San Andreas fault on the west and the Great Valley on the east. Tectonic processes relating to Pacific plate subduction gave rise to the California Coast Ranges and to exposure of peridotite-rich fragments of the Pacific Ocean crust and mantle and associated marine sediments, such as the Franciscan Group of Late Jurassic–Early Cretaceous age. Slices of Franciscan rocks and the peridotites, the latter having undergone pervasive alteration to serpentinite, have been incorporated and extruded into and over the Great Valley sedimentary sequence. Diapiric uprise of the serpentinite breached the Great Valley sediments sometime between late Oligocene and Early Miocene (Coleman, 1986; 2000). This serpentinite consists of a large amount of highly sheared and pulverized rock fragments and powders, as well as boulders of partially altered serpentine-rich rock. Coleman (1996, p. 19) regards the New Idria serpentinite body as "a unique geologic phenomenon created by plate tectonic evolution of western North America." He further states that "thousands of tectonic events acting on the serpentinite has produced a huge deposit of short-fiber asbestos by tectonic milling and recrystallization." Asbestos-bearing debris from the actively moving diapir has been entering the stream valleys for millions of years, and continues to the present day.

The average New Idria serpentinite rock contains 5 to 15 volume percent of this mineral (Mumpton and Thompson, 1975), but rock in the area in which the King City Asbestos Corporation is still actively mining contains up to 60% chrysotile asbestos The reserves of short-fiber chrysotile asbestos in the KCAC deposit are enormous. No amphibole asbestos has been reported in this serpentinite; its rarity is probably related to the absence of igneous intrusions within the serpentinite body.

Central and Southern Ural Mountains of Russia and Kazakhstan

The most important chrysotile asbestos deposits in Russia are within serpentinized gabbros, peridotites, and pyroxenites associated with the ultramafic ophiolite massifs of the central and southern Ural Mountains (Petrov and Znamensky, 1981; Spadea and Scarrow, 2000). The most productive mines are operated by the Uralasbest Company and are in the Bazhenovskoye district near Asbest City, 85 km east of Ekaterinburg

Figure 3. Mine Jeffrey, Asbestos, Quebec, Canada—the largest chrysotile open pit mine in the western hemisphere.

Figure 4. Photograph of the barren hillsides of the New Idria serpentinite, Coalinga, California. The serpentine is essentially a soft soil containing large amounts of chrysotile fiber, and is easily eroded by wind and rain.

(Shcherbakov et al., 2001). Since 1889, this one mine has produced >40 million tons of chrysotile asbestos, making Russia the greatest source of asbestos in the world, now surpassing in quantity that from all the mines in the Eastern Townships of Quebec (Ross and Vita, 2001). The Bazhenovskoye three-pit mine complex is >10 km in length (Fig. 5).

Two other large deposits of chrysotile asbestos associated with the serpentinized ultramafic rocks of the southern Urals are in the Dzhetygara District of northwestern Kazakhstan, 225 km southwest of Kustanay, and in the Kiembay District within the Orenburg Oblast of Russia. They are, after the Bazhenovskoye deposits, respectively, the second and third largest producing districts of the former USSR.

Northwestern Italy

Some of the asbestos deposits in northwestern Italy were known in Roman times. One of the most productive was the Balangero deposit, which is situated within the Balangero serpentinite ~40 km northwest of Turin. During the 1960s, chrysotile production was between 100,000 and 150,000 metric tons per year, but production declined in the 1980s and the mine closed in February of 1990 (Bowles, 1955, p. 47; Silvestri et al., 2001). The serpentinite formed from a spinel-plagioclase lherzolite and is interpreted as a satellite body of the Lanzo massif. The asbestos ore body contains massive, schistose, and highly fractured serpentinite rock. Long- and short-fiber chrysotile is present in the mine but only the short-fiber chrysotile is of commercial use. The short-fiber asbestos occurs as a stockwork of slip-fiber veins >2 mm thick (O'Hanley, 1996, p. 207).

At one time, tremolite asbestos was mined in some quantity from the ophiolites in the Susa Valley near the French border, as well as in Aosta Valley near Ivrea, Italy. Mining in the Aosta Valley started in 1865, but there has been little activity since 1905 (Bowles, 1955, p. 46–47).

Northern Greece

The most important chrysotile asbestos deposit in Greece, the Zidani Mine, is in a serpentinized dunite within the Pelagonian basement gneisses, which structurally underlie the Livadi ophiolite complex. The mine is 30 km south of Kozani, West Macedonia. Skarpelis and Dabitzias (1987) have reported that the chrysotile asbestos forms a "slickenfiber" coating on lens-shaped blocks of antigorite. The authors give evidence that the slickenfiber (slip-fiber) were originally veins of cross-fibers that, through subsequent deformation, had been recrystallized as slip-fiber coatings on the antigorite blocks. The Zidani mine and mill started operation in 1981, producing mainly slip-fiber. In 1996, production of asbestos was 60,000 metric tons. The mine recently closed, in part due to a lack of a European market for chrysotile asbestos.

Troodos Mountains, Cyprus

The Troodos ophiolite complex can be divided into (1) the ultramafic sequence consisting of serpentinized peridotites, tectonized harzburgites, lherzolites, and dunites overlain by (2)

Figure 5. The ridge between the south and central pit of the three-pit Bazhenovskoye Mining complex in Asbest City, Urals Region of Russia. This is the largest chrysotile mine in the world.

cumulate peridotites and gabbros (also referred to as the layered series); (3) the sheeted dike complex, composed of relatively fractionated basalts; (4) the extrusive sequence, composed of pillowed and nonpillowed lavas, which are overlain by (5) deep-water sediments (Glass, 1990; Robinson and Malpas, 1990). The commercial deposit of chrysotile occurs in heavily smashed and sheared serpentinized enstatite-olivinite rock, which covers at least two-thirds of the ultramafic area and occupies the highest part of the pluton around Mt. Olympus (Wilson, 1959, p. 79–80). Most of the chrysotile asbestos is the short-fiber type and occurs as a stockwork of cross-fiber veins as much as 15 mm thick. Slip-fiber has sometimes developed along shear planes. Although asbestos was mined in ancient times (probably within the Arakapas Forest area), modern development began only in 1904 and major production started after the First World War. Production for 1928 through 1957 averaged ~9,000 metric tons per year (Ingham, 1959, p. 160). In 1977, 40,000 metric tons were mined; by 1989 the mine was closed. Figure 6 shows three views of the now-abandoned Cyprus chrysotile asbestos mine, as well as some of the present reclamation activities.

From the descriptions of Wilson (1959), it appears that there is a significant amount of tremolite asbestos in the Troodos complex; for example, Wilson (1959, p.115) reports of "veins composed of a microcrystalline mat of tremolite." From our examination of occurrences of tremolite asbestos, particularly in the serpentinite belt of eastern North America, we suggest that these "mats" of tremolite reported by Wilson occur in a shear zone, the shearing causing nonfibrous tremolite to recrystallize into a fibrous mat of tremolite asbestos, sometimes referred to as "mountain leather." Further evidence of the occurrence of amphibole asbestos in the Troodos area was furnished by Dr. Eleni Geogiou Morisseau of the Geological Survey Department, Cyprus. She showed to us in November of 2000 a large sample of actinolite asbestos (Fig. 7) collected from a highly sheared serpentinite within the tectonized harzburgites of the Akapnov Forest area. These rocks lie within the Arakapas (transform) Sequence, an ophiolite complex separated from the main part of the Troodos Massif by the Arakapas transform fault (MacLeod, 1990).

EXPOSURE TO TREMOLITE ASBESTOS IN OPHIOLITE LOCALITIES IN TURKEY, GREECE, CYPRUS, CORSICA, AND NEW CALEDONIA

In the discussion that follows, six ophiolite localities are described where the residents of rural villages were exposed to tremolite asbestos through its use as ingredients for stucco and whitewash. Exposure to the tremolite asbestos dusts has caused a significant number of mesothelioma cases in these villages. The published data do not give enough geological and mineralogical details to pinpoint the exact source of the tremolite asbestos, but we suggest that the tremolite asbestos appears within the ophiolite complexes at the contacts of the various later stage intrusions, and in shear and fault zones open to hydrothermal fluids. It would be important for geologists to visit the sites where the tremolite asbestos was quarried in order to obtain an exact description of the petrologic relationships between the tremolite asbestos and the host rocks, and to confirm that asbestos mineral in question is indeed tremolite and not some other type of amphibole.

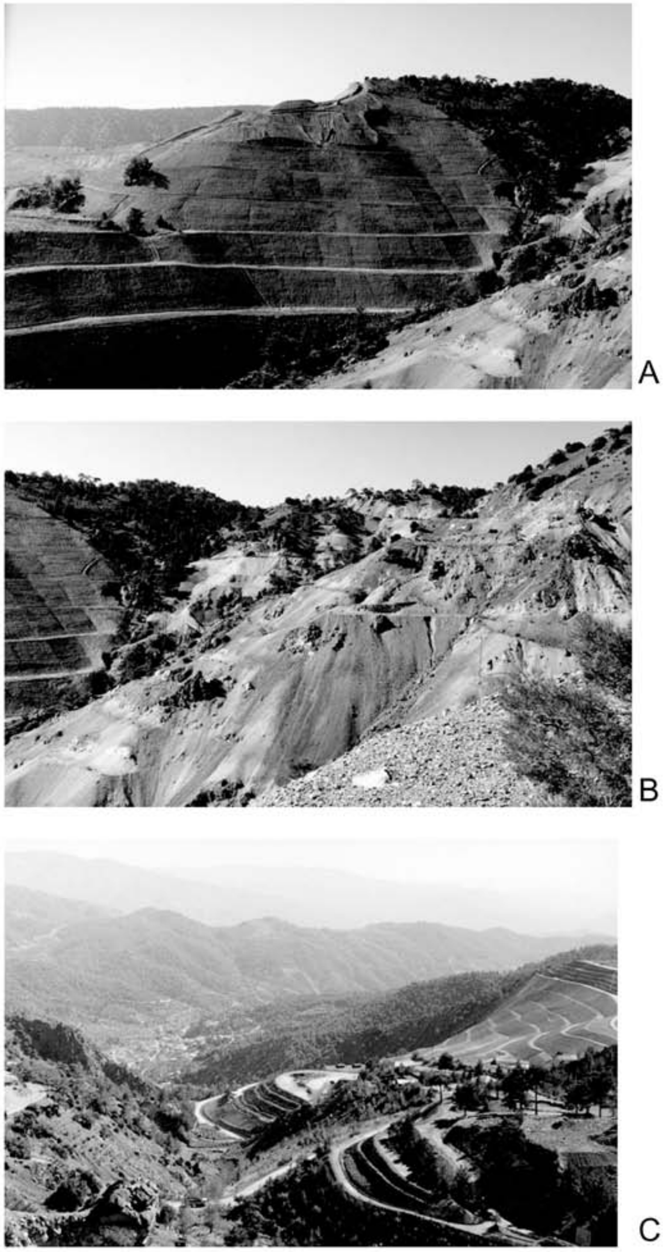

Figure 6. Remediation work in progress on the now-closed Cyprus chrysotile asbestos mine. A: Photograph of engineering work involving lowering the angle of repose of the talus slopes by the construction of an intervening series of benches between the slope sections. B: Photograph of to-be-stabilized talus slopes (right) and stabilized slopes and benches (left). C: Photograph of partially completed slope and bench reconstruction (right), as well as a view down the stream valley toward the town of Kato Amiantos (left center).

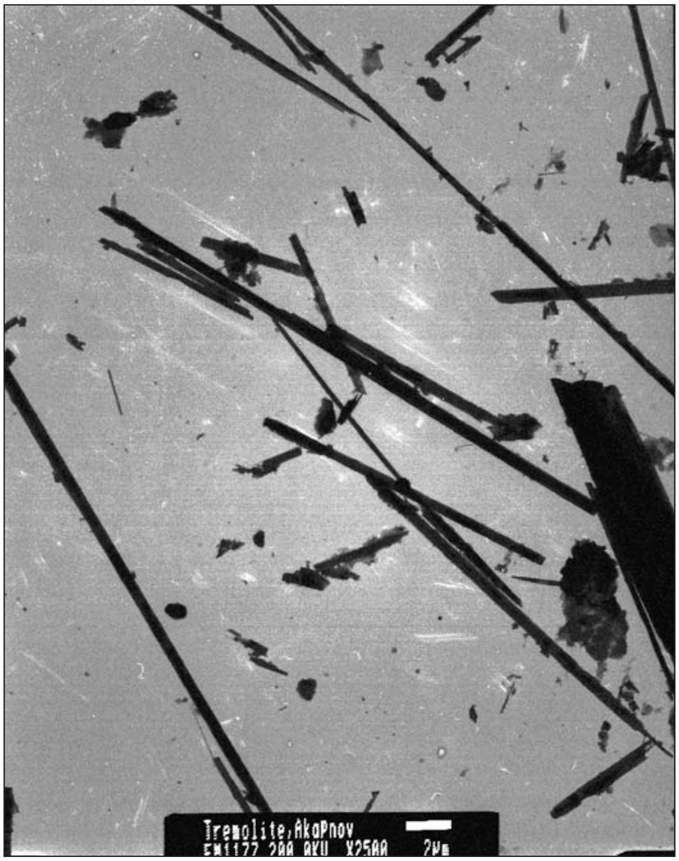

Figure 7. Transmission electron photomicrograph of tremolite asbestos from Akapnov Forest, Cyprus.

Guleman and Killan Group Ophiolites within the Maden Complex, Turkey

Yazicioglu et al. (1980) reported on 41 patients having respiratory cancer that were admitted to the Diyarbakir Chest Hospital, Diyarbakir, Turkey, from 1977 to 1978. Of these 41 cases, 23 and 18 were cancers of mesothelial tissue and lung, respectively. Of these, 22 of the mesothelioma and 11 lung cancer cases came from the “asbestos” villages of Çermik, Ergani, Çüngüs, Maden, and Siverek, whereas one mesothelioma and seven lung cancer cases came from the “non-asbestos” villages of Lice, Kulp, Dicle, Hani, Silvan, Harzo, and Çinar. The extraordinarily high incidence of mesothelioma among both genders in the five “asbestos” villages of very low population strongly suggested that the villagers were exposed to asbestos environmentally. It was discovered that tremolite asbestos was used locally to make a whitewash or stucco for the walls, floors, and roofs of houses.

The whitewash contained fibrous tremolite and the nonfibrous minerals talc, chlorite, antigorite, and lizardite. Although occasional chrysotile fibers were found in the environment, Yazicioglu et al. (1980) attributed these mesothelioma cases occurring in the Çermik village region to exposure to tremolite asbestos. The tremolite asbestos was quarried in the nearby mountains by the male population for local use and for sale elsewhere. Women then ground the asbestos ore into a powder and mixed the powder with water to form a slurry for application to buildings. This process was repeated every year; consequently the homeowners were repeatedly exposed to tremolite asbestos dusts from an early age. We note that these five “asbestos” villages are located within or a few kilometers from the Guleman and Killan Group ophiolites that form part of the Maden Complex. Aktas and Robertson (1990) describe the Killan Group as consisting of serpentinized peridotite, gabbro, dolerite, basic pillow lava, and pelagic sediments. These observations strongly suggest that the tremolite asbestos was quarried within one or more of the rock units within these complexes.

Ankara Ophiolite, Turkey

Apparent asbestos-like diseases of the chest, including mesothelioma, have also been reported in the small Anatolian Village of Çaparkayi in the Sabanözü area of the Çankiri district, Turkey (Baris et al., 1988a, 1988b). Four cases of pleural mesothelioma were reported in a population of 425 over a three-year period. All of the tumors occurred in women between 26 and 40 years of age. The non-occupational nature of exposure is indicated by the tumors occurring at a young age and in women. Although there is no asbestos mine near this village, the villagers commonly used white stucco described by Baris et al. (1988b, p. 838, fig. 2) as “rich in tremolite asbestos including some very fine fiber.” The Baris report indicates that the high incidence of mesothelioma and some of the lung and pleural tissue abnormalities in the village are associated with exposure to tremolite fibers. The villages of Sabanözü and Çankiri lie a few kilometers west and east, respectively, of the Eldiven Dagi, a mountainous area that lies within the Ankara ophiolite mélange belt of northern Anatolia (Tankut and Gorton, 1990, fig. 1). We suggest that the residents of Çaparkayi, and probably residents of nearby villages, obtained the stucco ingredients from veins of tremolite asbestos occurring within the Ankara ophiolite complex.

Pindos Ophiolite, Greece

Six out of the seven reported deaths (3 males and 4 females) from malignant pleural mesothelioma occurred among residents of the villages of Milea, Metsovo, Anilio, and Votonosi. These villages are located in the Pindos mountain region of northwestern Greece. Of the 268 people who underwent X-ray examination, 46% showed some pleural change, including bilateral pleural plaques, pleural thickening, and restrictive lung function. These lung changes and the mesothelial cancers constitute the cluster of disease referred to as “Metsovo lung” (Constantopoulos et al., 1985, 1987; Langer et al., 1987). Biopsy of the lung tissue in the mesothelioma cases, as well as others with pleural disease, contained tremolite asbestos fibers. Also, soil, whitewash, and settled dust samples from Metsovo showed the presence of tremolite asbestos (Langer et al., 1987). Before 1940, virtually all of the inhabitants of the Pindos area applied tremolite asbestos-bearing whitewash to their homes. The village of Metsovo is located within or very near to the Pindos ophiolite. Rassios and Smith (2000, p. 475–476, figs. 2, 4) describe the Pindos ophiolite as having an outcrop area of >1300 km^2. It contains harzburgite units lying above a metamorphic sole composed mainly of amphibolites. In addition, they describe intrusions of pyroxenite and gabbro dikes and cumulate plagioclase dunite and troctolite sills. We suggest that the tremolite asbestos is associated with some of the igneous intrusions or mélanges within the ophiolite complex and was quarried in the past for the special use in stucco, whitewash, and other building materials.

Troodos Ophiolite, Cyprus

McConnochie et al. (1987) reported on a health study over the period 1969–1986 of 14 residents of Cyprus, several of whom had lived in mountain villages near the Troodos asbestos mine. All 14 cases were initially reported to have died of mesothelial cancers, although a complete pathological examination verified only seven of the deaths (four male asbestos miners, and one male and two female non-miners) as due to mesothelioma. It was inferred that the disease was caused by asbestos dust from the mine; however, McConnochie et al. suspected that tremolite asbestos was the cause of the mesotheliomas because analysis of the lung tissue of two humans and six sheep (residing within five miles of the mine) indicated that both chrysotile and tremolite asbestos were present in the tissue. Proper identification of the amphibole minerals is suspect because “crocidolite” was also reported to occur in the sheep lung tissue. “Crocidolite” has never been identified in an ophiolite complex. Another peculiarity is that no tremolite asbestos was found in the samples taken from the Troodos mine, although tremolite asbestos was found in environmental dust samples taken from two “roof caves” in two villages. McConnochie et al. (1989) report that stucco used in the Troodos region contained fine fibrils of chrysotile and long, thin tremolite fibers. In our visit to Cyprus in November 2000, we searched unsuccessfully for evidence of the use of tremolite asbestos in whitewash and stucco. We found, rather, that the whitewash presently used on fruit trees as an insect repellent is asbestos-free. The tremolite asbestos was perhaps used sporadically in the mountain villages of Cyprus many years ago, thus a few mesothelioma cases may have resulted from exposure to this mineral, but whether there is still a danger from exposure to tremolite asbestos in Cyprus remains to be seen. We, however, have noted that fibrous amphiboles are present in the Troodos complex.

Corsican Ophiolite Sequences

Rey et al. (1993, 1994) found pleural plaques in 41% of the residents of the northeastern Corsican village of Murato, situated in an area underlain, according to the authors, by tremolite and chrysotile-bearing rocks. Only 7.5% of the residents of the “control” village (Vezzani, located in an area that is not underlain by asbestos-bearing rocks) were diagnosed as having pleural plaques. Rey et al. (1993) also state that 13 cases of environmental mesothelioma have been recorded in Corsica since 1980. Airborne levels of tremolite asbestos (Rey et al., 1993, table 3) were much higher in Murato (6 to 72 ng/m^3) than in Vezzani (0.4 to 1.0 ng/m^3), but the chrysotile levels in the two villages were similar (Murato, 0.3 to 1.0 ng/m^3; Vezzani, 0.1 to 0.3 ng/m^3). Rey et al. (1993, fig. 1) give a generalized map showing the villages of Murato and Vezzani and areas containing “surface deposits of asbestos.” Major ophiolite sequences are found in northeastern Corsica, including the Balagne and Nebbio nappes. Murato is situated very near the Nebbio nappe, with outcrops of serpentinite and metagabbro, whereas Vezzani appears to be located within calcschist terrane (see Brunet et al., 2000, figs. 4 and 5). The papers by Rey et al. (1993, 1994) do not account for the source of the airborne asbestos, but do mention the existence of a chrysotile asbestos mine at Canari that closed in 1965. The town of Canari is also near the Nebbio nappe.

New Caledonia Ophiolite

The Pacific island of New Caledonia contains a major ophiolite body that was emplaced mainly during the Oligocene (Gealey, 1979, fig. 6, p. 230). Coleman (1971, p. 1216) reports, “Large plates of ultramafic rock, consisting primarily of dunite and harzburgite, cover large areas of New Caledonia.” Coleman further states that “serpentinite is developed mainly along the thrust contacts; the massive peridotite slabs show 10%–20% serpentinization.” Luce et al. (2000) report a high incidence of lung disease in New Caledonia. During the period 1993–1995, 15 pleural mesotheliomas (9 female and 6 male), 1 peritoneal mesothelioma, 228 lung cancers, and 28 laryngeal cancers were diagnosed. The risk of pleural mesothelioma was strongly associated with the use of a whitewash (referred to locally as pö) composed of very friable rock derived from local outcroppings. From 1930 to the end of the 1960s, pö was used to coat indoor and outdoor walls of houses (Luce et al., 2000, p. 259). The whitewash, suspended in water during application, was found to consist of nearly pure tremolite asbestos. All 9 of the female and 5 of the 6 male pleural mesothelioma cases had been exposed to the tremolite asbestos. The association of mesothelioma with ophiolite complexes is again indicated.

REMEDIATION AND RECLAMATION INITIATIVES IN AREAS CONTAMINATED WITH ASBESTOS

Asbestos contamination in various geographic localities, particularly in the United States, has generated great concern and has prompted, in some cases, very costly remedial actions. In the following five cases we will describe: (1) the geological occurrence of the asbestos and exposures that initiated the remediation activity, (2) the health effects (if any) that may have appeared in those exposed, (3) and the remediation and/or reclamation activities that were instituted.

Libby, Montana, Asbestos-Bearing Vermiculite Deposit

The Rainy Creek Complex is an igneous alkaline-ultramafic body that has intruded into the sedimentary rocks of the Precambrian Belt series. The complex is located in Lincoln County, Montana, near the town of Libby, and at one time hosted the world's largest vermiculite mine. The mine opened in 1923, and was owned and operated by the W.R. Grace Company from 1963 until it closed in 1990. The ultramafic unit of the complex is biotitite (composed mostly of very coarse grained biotite) surrounded by a biotite pyroxenite. Later magmatic events altered the biotite to hydrobiotite and vermiculite. About 35% of the complex is composed of various alkaline rocks, syenites, trachytes, phonolites, and granites (M. Gunter, University of Idaho, personal commun., 2002). The alkaline units of varying widths pervasively intrude and cut across all of the ultramafic rocks.

In a report on the Libby vermiculite deposits, Bassett (1959, p. 285) states that "mine workings have exposed numerous thin syenite dikes, ranging from a few inches to several feet thick, which cut the pyroxenite." He also states that "the asbestos is also found disseminated through the intrusive as thin layers along cleavage planes of the augite" (p. 287; see also Fig. 4 and 6).

Gunter et al. (2001) have carefully reexamined the mineralogy of the Rainy Creek Complex, and find the fibrous mineral to be the amphibole mineral winchite, which agrees with a previous study of a winchite sample from Libby by Wylie and Verkouteren (2000). Colloquially, this fibrous amphibole could be referred to as "sodic tremolite" but official amphibole nomenclature places it in the chemical category of winchite (Leake et al., 1997). End-member winchite has the chemical formula $CaNaMg_4(Al,Fe^{3+})Si_8O_{22}(OH)_2$. Although the Rainy Creek Complex is not an ophiolite, there is one similarity—the presence of numerous secondary intrusions into the ultramafic body in the form of dikes and veins.

Concern over the health effects of the winchite dust particles was brought to national attention by newspaper articles (e.g., Living and Dying in Libby, Spokesman-Review, Spokane, Washington, November 22, 2001, p. 1–10) and by an investigation by the U.S. EPA of the W.R. Grace mining and milling facility. An epidemiological study by McDonald et al. (1986) showed that the Libby vermiculite miners and millers had an increased risk of lung cancer (SMR = 2.45) and non-respiratory disease (SMR = 2.55). Recently, McDonald et al. (2001) have updated this mortality study and have reported in the study cohort a continuing excess mortality due to lung cancer and 12 mesothelioma cases among 285 deaths. Mesothelioma mortality now accounts for 4.2% of the deaths among the vermiculite miners. The amphibole fiber implicated in disease is erroneously reported in medical literature and newspaper articles as tremolite asbestos rather than its true identification—asbestiform winchite.

The Agency for Toxic Substances and Disease Registry report on the health of the residents of Libby and environs (ATSDR, 2000) states that 11 deaths (10 male, 1 female) were due to asbestosis. This ATSDR report also states that elevated lung cancer and mesothelioma mortality could not be verified in those with non-occupational exposure. Another ATSDR report (ATSDR, 2001) states that a radiological study of 5590 Libby residents determined that 18% had "pleural abnormalities." Various commentaries suggest that the winchite fiber dust has been pervasive for at least the last 75 years throughout the Libby area. If the fiber levels were elevated, for example, as in New Caledonia, then a significant increase in lung cancer incidence and numerous cases of mesothelioma would be expected among the Libby residents, on the basis of the health experience of the villagers who processed tremolite asbestos for stucco and whitewash. The W.R. Grace Company declared bankruptcy in April of 2001, in part because of potential remediation costs and pending lawsuits.

New Idria, California, Superfund Sites

The New Idria serpentinite near Coalinga, California (Fig. 4) is the site of three chrysotile asbestos mines, two of which (Atlas and Johns-Manville) ceased operation many years ago. The KCAC mine remains operational. The two abandoned mine sites are now designated as U.S. Environmental Protection Agency Superfund sites because of the Agency's concern about the health hazard of water- and air-borne chrysotile asbestos emissions from the old mine pits; however, the two Superfund sites cover only a few percent of the 114 km^2 asbestos outcrop area of the serpentinite. Asbestos-bearing dust and debris has been entering the air and the stream valleys from the entire area for millions of years. The EPA has chosen to focus on a small fraction of the asbestos releasing area, rather than develop a scientifically based policy that addresses the entire outcrop area (Ross, 1994; Coleman, 1996).

The medical and scientific evidence suggests that ingestion of asbestos increases the risk of gastrointestinal cancer only very slightly, if at all (Ross, 1984; Graham, 1981). In a recent review on mesothelioma occurring from non-occupational or low-dose asbestos exposure, Hillerdal (1999, p. 508) states: "most ingested mineral fibers will never be absorbed but be cleared in the normal way, and the harmful effects of asbestos in drinking water or drinks is probably minuscule (and much smaller than the risk of drinking alcohol)." It is noted that much of the pulmonary clearance of inhaled asbestos fibers in occupationally exposed workers ultimately took place through the gastrointestinal tract.

Even among those with occupational asbestos exposure, the increase risk of gastrointestinal (GI) cancer remains controversial and the results of epidemiological studies have not been consistent in finding that there was an increased risk of this cancer in the various cohorts studied. Furthermore, where an increased risk does exist, it is not associated with a dose-response. The risk of GI cancer does not increase with increasing exposure, which weakens the association between the agent and the disease (Gamble, 1994; Weiss, 1995).

Epidemiological studies of human populations having higher than usual intake of asbestos-containing water have not shown an increased risk of gastrointestinal cancer or any asbestos-related disease for that matter. The World Health Organization and other national and international health organizations have been remarkably clear on the extremely low risk of health effects from asbestos in water. The World Health Organization (WHO, 1986, p. 129) stated: "the studies conducted to date provide little convincing evidence of an association between asbestos in public water supplies and cancer induction." Further, as the U.S. EPA stated in a press release of January 7, 1991, "there is no evidence that ingestion of chrysotile asbestos causes harm, either in man or animals."

Inhalation of chrysotile asbestos fibers in the quantities found in the New Idria area certainly must be a minimal risk. This statement is supported by noting, as described above, the lack of asbestos-related disease among asbestos trades workers and the women living in the asbestos mining towns of Quebec who were exposed to low to moderate amounts of chrysotile asbestos. New Idria Superfund sites, even by expenditure of very large sums of money, will have no measurable effect on human health, particularly in view of the fact that most of the asbestos emissions come from areas outside the Superfund sites, through naturally occurring processes.

Fairfax County, Virginia Building Sites

In 1987, asbestos was discovered in a construction site in Fairfax County, Virginia, USA, causing concern over possible health effects to workers as well as to county residents. Avery A. Drake and Malcolm Ross, then of the U.S. Geological Survey (USGS), examined the site and found actinolite asbestos within a rock formation that composed part of the Piney Branch Complex (Drake, 1986). The asbestos was the slip-fiber type and was confined to the shear zones and anticlinal folds within an actinolite schist, a prominent rock type within the complex. Drake and Morgan (1981) state that the Piney Branch Complex, which outcrops over a 9 km^2 area of Fairfax County, consists of highly altered peridotite, pyroxenite, and gabbro, and further suggest it is a mélange that resulted from deformation of a layered complex, and closely resembles ophiolite material that crops out in nearby Maryland and southern Pennsylvania. Prominent tremolite asbestos veins were also observed by one of us (Ross) within one of the serpentinite bodies in Montgomery County, Maryland, USA, a sample of which is shown in Figure 8.

Some of the Fairfax County rock samples contained appreciable amounts of actinolite asbestos and, as a result, the Fairfax County Health Department initiated dust control procedures and published a dust control advisory (Dusek and Yetman, 2002). The advisory requires contractors to use proper dust control

Figure 8. Photograph of a tremolite asbestos sample collected from a large vein within a serpentinite, Montgomery County, Maryland, USA. Pen for scale is 14 cm long.

practices, air monitoring, safe waste rock disposal, and requires that sufficient notice of possible asbestos contamination be given to all employees and contractors in compliance with existing asbestos standards. The county advisory further states that construction need not be banned, but that six procedures must be established for dust suppression. As a result of this well-reasoned regulatory initiative, Fairfax County continued to build housing and commercial buildings on some of the most valuable land in the eastern United States, while at the same time protecting the workers and the public from an avoidable risk of asbestos-related disease. Soon after the discovery of asbestos, the local newspapers (e.g., *The Washington Post*, August 15 and September 29, 1987) gave factual statements about the asbestos occurrence in Fairfax County, but did not promote undue alarm, thus allowing the County officials to control asbestos exposures while allowing continued real estate development.

Although there was little asbestos mining in Virginia, Maryland, and Pennsylvania, there existed several quarries that processed serpentine rock for various construction purposes. One of these quarries, the Hunting Hill quarry, near Rockville, Maryland (Fig. 9) came into prominence in 1977 when chrysotile fibers were detected in various places near the quarry. A report in *Science* by Rohl et al. (1977) aroused much concern, causing the Montgomery County (Maryland) government to introduce various medical, regulatory, and abatement initiatives, such as paving over the serpentine gravel roads and checking the local hospitals for mesothelioma cases. The predicted epidemic of asbestos-related disease did not materialize—as would have been expected from the health data for the residents of the Quebec asbestos mining towns—and two years later the asbestos problem was nearly forgotten and the quarry continued to operate.

El Dorado County, California, Housing Developments

The Great Valley ophiolite belt parallels the western side of the Great Valley of California for at least 400 km (Coleman, 2000, Fig. 1). This ophiolite belt includes numerous outcrops of serpentinite, which were sites of at least 26 asbestos mines or asbestos prospects. Four of the mines were major producers of chrysotile asbestos, the most important of which was the Calaveras mine (Fig. 10), now closed, located near the town of Copperopolis. Two of the prospects, one at Iowa Hill in Placer County and the other in the Murphy area of Calaveras County, contained slip-fiber tremolite asbestos (Chidester and Shride, 1962). During the 1990s, many new housing projects were started in the fast-developing foothills area of El Dorado County, California, a county located within the Great Valley ophiolite belt. During excavation for housing sites, apparently within serpentinite rock, fragments of tremolite asbestos were found at some of the sites, alarming the homeowners. The

Figure 9. The Hunting Hill serpentinite quarry, near Rockville, Maryland, furnishes crushed stone to the Washington, D.C., metropolitan area. The quarry came into prominence in 1977 when chrysotile fibers were detected in dust emissions.

press, particularly the *Sacramento Bee*, Sacramento, California, produced a series of articles that suggested that the county residents' exposure to asbestos was endangering their health. A large number of air samples were collected at numerous sites all over the county by the California Air Resources Board (CARB). A detailed listing of the fiber concentration, which averages less than 0.001 f/ml, can be obtained at the CARB website (http://www.arb.ca.gov/toxics/asbestos/monitoring.html). The website tables do not identify the mineral fibers because apparently the CARB considers all fibers to be equally dangerous. Additional data released by the CARB shows that tremolite fiber has not been found in the air samples. El Dorado County appears to remain in turmoil over asbestos, unlike Fairfax County, Virginia, where the asbestos controversy—if indeed there was a controversy—died out 10 years ago.

Reclamation of the Troodos Asbestos Mine, Cyprus

The chrysotile asbestos mine occupies the eastern slopes of the Troodos massif in the neighborhood of the asbestos mining village of Pano Amiantos. The mine property, including large areas of rock waste, covers an area of ~10 km^2 at an elevation of nearly 1500 m. Pano Amiantos, currently containing 84 mostly unoccupied buildings, was originally located near the mine, but with later expansion the mining complex eventually surrounded the village. A second village, Kato Amiantos, has a current population of ~300 people and is located 2 km down the valley and 500 m below the mine site. Members of the Cyprus Parliament expressed concern about the possible landslide and health hazards associated with the mine property, but there was also a desire to reclaim this property for recreational use because it is close to the beautiful Troodos National Forest Park. This concern, under the leadership of the Geological Survey and Forest Departments of Cyprus, prompted the initiation of an extensive project to reclaim the mining property for recreational use.

We visited the mining site in November of 2000 to observe the beginnings of this remarkable reclamation activity (Fig. 6). Of particular importance, in addition to reducing mineral dust emissions, was the reduction of the steep angle of repose of the waste rock around the mine site. The steep slopes created a significant landslide hazard, particularly for the residents of Kato Amiantos. Stabilization of the mine property was accomplished by: (1) reducing angle of repose the waste rock slopes, (2) constructing benches within the slopes, (3) covering the benches and slopes with a few centimeters of non-serpentinite-bearing soil to give added nutrients for the vegetation, (4) covering the added soil with old tree cuttings to reduce erosion, and (5) planting a large variety of plants and trees indigenous to serpentinite soils, not only to prevent soil erosion but to enhance the beauty of the region noted for its pine forests.

Figure 10. The Calaveras asbestos quarry, El Dorado County, California. Now closed, the quarry at one time was a major producer of chrysotile fiber.

SUMMARY

Ophiolite complexes, including the associated serpentinite belts, are found in many parts of the world and it was in these rocks that asbestos was first discovered in Cyprus, Greece, and Finland as long as 5,000 years ago. Chrysotile asbestos is by far the most common asbestos mineral, generally occurring in most serpentinites. The richer deposits contain several volume percent of this mineral. In addition to chrysotile, the amphibole asbestos minerals anthophyllite, tremolite, and actinolite are found in ophiolite complexes. Anthophyllite asbestos was mined mostly within the ophiolite complex located in the Paakkila area of East Finland. Tremolite and actinolite asbestos were mined sporadically in many areas of the world, but total production was very low. We estimate that ~85% of the commercially produced asbestos came from ophiolite complexes. Some of the major chrysotile asbestos mines are located in Quebec, Canada; in the central and southern Ural Mountains of Russia and Kazakhstan; near Coalinga, California, USA; in northern Italy and Greece; and in the Troodos mountains of Cyprus. Two other amphibole asbestos minerals, "amosite" and "crocidolite," were important commercially but are found only in banded iron formations.

The asbestos minerals crystallize under special conditions within rocks formations that are undergoing intense deformation characterized by faulting, shearing, and dilation, and accompanied by intrusions of magmatic fluids in the form of dikes and sills. The fibers crystallize in zones of deformation and at igneous intrusion-host rock contacts. Highly tectonized ophiolite complexes contain many of these deformation features, thus presenting conditions ideal for fiber formation. Slip-fibers are formed within the fault and along shear planes, whereas cross-fibers form within dilation zones.

The asbestos-related diseases—asbestosis, lung cancer, and mesothelioma—have taken a huge toll on the lives of asbestos trades workers and asbestos miners and millers. Epidemiological studies of large cohorts of asbestos workers, exposed to variable amounts of chrysotile, and amphibole asbestos, show that the amphibole asbestos dusts are more dangerous, with "amosite" and "crocidolite" accounting for most of the mesothelioma mortality. Epidemiological studies show that low to moderate exposure to chrysotile asbestos presents a very low health risk. Although conventional epidemiological studies of tremolite and actinolite asbestos have not been possible because of the difficulty of assembling a large enough cohort of exposed individuals to be statistically significant, there are several "prevalence" studies where an unusually large number of people within a small geographic area died of mesothelial cancers. Six of these areas include small villages in Turkey, Greece, Cyprus, Corsica, and New Caledonia. Residents of several of these villages have been exposed to tremolite asbestos quarried from nearby local rock formations. It was used as an ingredient for stucco and whitewash, which was applied to the wall surfaces of the village buildings. All these villages lie within or near to ophiolite complexes where amphibole asbestos is likely to occur.

The presence of tremolite and actinolite asbestos in ophiolite complexes in Fairfax County, Virginia, and in El Dorodo County, California, has caused concern over the possible health effects that these mineral dusts may have on the local residents. The county governments of the two communities have instituted various regulations governing construction practices, but with differing results related to how the health risks are presented to the public by the county officials and by the local newspapers.

Two abandoned asbestos mine sites within the New Idria serpentinite near Coalinga, California, are now designated as U.S. EPA Superfund reclamation areas because of the concern about the health hazard of chrysotile asbestos. The two sites cover a few percent of the 114 km^2 that encompass the total outcrop area of the chrysotile-rich serpentinite. The expenditure of many millions of dollars for site reclamation will most likely have no measurable effect on human health, for most of the asbestos emissions comes from areas outside the Superfund sites through naturally occurring processes. In contrast, the government of Cyprus has started reclamation of the Troodos chrysotile asbestos mine property occupying a 10-km^2 area where asbestos emissions are likely to originate.

An igneous alkaline-ultramafic complex located near the town of Libby, Montana, hosts a large vermiculite mine once owned by the W.R. Grace Company. The very fibrous amphibole winchite, very similar in morphology to tremolite asbestos, is pervasive throughout the complex. Concern over the health effects of the winchite fibers disseminated from the mine workings to the surrounding areas was brought to national attention by newspaper articles and by an investigation of the mining and milling facility by the U.S. EPA. As a result of potential reclamation costs, property damage, and personal injury lawsuits, the W.R. Grace Company declared bankruptcy in April of 2001.

DISCUSSION AND CONCLUSIONS

We must conclude from the vast literature published on health effects of minerals that the inhalation of any biopersistent mineral that crystallizes as long thin fibers with widths of 0.5 micrometers or less and lengths of >5 micrometers could potentially be a health hazard. Evidence for this includes environmental mesotheliomas associated with exposure to tremolite asbestos and other fibrous minerals, such as the zeolite erionite. Chrysotile asbestos is an exception because low to moderate exposure to this mineral, even over long periods, presents a very low health risk.

The "fiber hypothesis" should include an understanding of the range in carcinogenic potency that particular mineral fibers can possess. Low concentrations of fibrous minerals are common in nature, but environmental disease related to mineral fiber is rare and mainly due to a few types of amphibole asbestos and fibrous eronite. The scientific and medical information available does not justify the claim that exposure to any amount of any fiber presents an unacceptable health risk. If this claim were true, rocks containing any concentration of any type of fibrous mineral would be off limits for any kind of mining or other types of activity, and thus would restrict the use of vast areas of geologic terrane needed for sustainable development. We should, however, promote a policy that not only protects the miners, construction workers, and local inhabitants, but also allows for various types of mining and commercial development. Regulations such as those promulgated by the county government of Fairfax, Virginia, can serve as a model for using science as a basis for risk management decisions to control mineral fiber dust exposures, while allowing mining and other development activities. Over-regulation can be extremely costly, addresses minimal health risk, and diverts attention from more socially important endeavors (Wilson and Price, 2001).

There is now ample evidence that dust levels now maintained in the chrysotile asbestos mines of Canada and Russia (Shcherbakov et al., 2001; Wilson and Price, 2001), coupled with similar low dust levels maintained in other workplaces, present health risks that are indistinguishable from risks associated with substitute materials, such as fiberglass, rock wool, and various composites; however, legal reform and education of the media and general public are needed to bring a scientific basis to public policies regarding exposure to fibrous particulates.

In the study of ophiolite complexes, we should take particular note of the faults, shear zones, folds, and igneous intrusion-host rock contacts for the presence of amphibole asbestos, and suggest that the local authorities discourage its use for commercial purposes. In rocks such as those found in Libby, Montana, where the fibrous mineral appears to be disseminated throughout the vermiculite ore body, exploitation of the mineral resource may not be possible unless very careful mineral beneficiation procedures are instituted; however, where the asbestos-bearing veins are dispersed between larger volumes of uncontaminated ore, it should be possible to "mine around" the fiber-bearing rock and dispose of it as waste. As a final comment, it would very helpful if there could be more cooperation between medical scientists and geoscientists in health studies where mineral dusts are of concern.

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