10th Anniversary Critical Review: Naturally occurring asbestos†

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Asbestos is a naturally occurring mineral in the Earth's crust, and it is not confined to the historic and current asbestos mining areas, but rather quite commonly encountered in certain geological environments across the world. That diseases developed as a result of high exposures suffered by miners and asbestos products workers is incontrovertible. In addition, asbestos contamination as a result of past production and use is considered a serious issue where remediation is normally required. However, the risk to health of living on soil and rock where asbestos is encountered as a result of the natural occurrence of small quantities of asbestos minerals is less obvious. The picture becomes even less clear when the minerals are subject to intensive investigation, since our generally accepted definitions of asbestos are themselves put to the test. The discovery of asbestos or related minerals has consequences beyond any immediate risks to health, including profound effects on the value of and ability to use or enjoy property. This review examines the issue of naturally occurring asbestos (NOA) as it has developed in the United States of America and elsewhere, including some superficial insights into the reactions of communities to the presence of NOA. These responses to 'contamination' by nature deserve further in-depth study.

Introduction

Asbestos is defined as certain minerals that have crystallized in a finely fibrous habit, in bundles of easily separable fibers and/or fibers which are composed of smaller diameter fibrils, and with a hair-like elongated shape resembling organic fibers, with exceptionally smooth faces and displaying unusual adamantine or silky luster.[1] Asbestos historically includes the serpentine mineral chrysotile (the commonest type of asbestos used commercially), and the amphibole minerals crocidolite (which is the asbestiform version of the mineral riebeckite) and amosite (the asbestiform version of the mineral series cummingtonite-grunerite), along with asbestiform tremolite-actinolite (tremolite asbestos, actinolite asbestos) and asbestiform anthophyllite (anthophyllite asbestos) (Table 1). The term 'asbestos' was defined by industry to refer to the minerals being exploited (for example, the term 'amosite' is actually derived from the acronym of the Asbestos Mines of South Africa). More recently, it has been noted that minerals not in this list may also have an asbestiform habit, even if they have never been exploited. The properties that made these minerals commercially useful included the occurrence of very long, thin fibers in bundles, with great flexibility, high tensile strength, and heat and acid resistance. Unfortunately, it is a similar list of properties that are thought by some to be the main contributors to the toxic effects of inhaled fibers.[2] Asbestos has been implicated in a pneumoconiosis ('asbestosis') resulting from exposure to relatively large airborne concentrations in the workplace rarely encountered today. Lung cancer and mesothelioma are the diseases of greatest current environmental concern, although the present high rates are a consequence of excessive occupational exposures in the past and the long latency period before manifestation of disease.

Over 90% of the historic world asbestos production has been of chrysotile.[3] Chrysotile is mineralogically very different from the amphibole minerals, and it has been suggested that the mesothelioma hazard from exposure to chrysotile is a reflection of its contamination by amphibole minerals.[4] The relative potency for chrysotile compared to amphibole asbestos in the

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Table 1 Summary of minerals where fibrous crystal form or cleavage has generated concern (not an exhaustive list)

Mineral	Asbestiform or fibrous probability	Remarks
Serpentine minerals		
Chrysotile	Always	Most common type of asbestos; almost the only form mined today
Antigorite	Rare	
Amphibole minerals		
Riebeckite	Probable (crocidolite)	Previously mined as asbestos in South Africa, Australia and Russia, but not common elsewhere
Cummingtonite-grunerite	Probable (amosite)	Previously mined as asbestos in South Africa. Non-asbestiform habit is common
Tremolite-actinolite	Probable	Widespread occurrence both as asbestiform and non-asbestiform habits, but only rarely mined as abestos
Winchite-richterite	Probable	Rarely encountered
Anthophyllite	Probable	Previously mined as asbestos in Finland and in the eastern USA. Often associated with talc.
Arfvedsonite, fluor-edenite, etc.	Possible	Rarely encountered
Zeolites		
Erionite, mordenite	Almost always fibrous	Not considered as asbestos, rarely encountered
Clay minerals		
Palygorskite, sepiolite	Fibrous habit possible or common	Not considered as asbestos, rarely encountered
Others		
Brucite, wollastonite, talc, balangeroite	Fibrous habit possible or common	Not considered as asbestos, and, except for talc, rarely encountered

induction of lung cancer has also been questioned (the 'Amphibole Hypothesis'); an extensive discussion of this issue is outside the scope of this review and has been published elsewhere.[5] Current production of asbestos is still mostly chrysotile, particularly from deposits in Russia, Kazakhstan and China, at least some of which has been reported as being relatively free from amphibole contamination, although this may not actually be the case.[6] Asbestos in Russia was discovered in 1884 and has been worked since 1886. All kinds of asbestos have been mined, including anthophyllite and the asbestiform habit of the amphibole mineral arfvedsonite, although amphibole asbestos was mostly used in military applications. Chrysotile was the major product, and is the only product today, mostly from the Bazhenovskoye deposit at the city of Asbest, near Ekaterinburg (formerly Sverdlovsk) in the Ural Mountains. Asbestos disease related to chrysotile extraction and product manufacture has been studied extensively. High airborne dust concentrations in the past were linked with asbestosis and lung cancer. The incidence of mesothelioma in the region where the asbestos industry is located is higher than average for the Urals, but the disease is still considered relatively rare.[7] There is also possible evidence of elevated disease rates from Russian asbestos product operations outside of Russia, such as at Szczucin, in Poland.[8] This situation may require further study. Canada, one of the largest sources of asbestos in the past, still produces some chrysotile, but now only intermittently. Zimbabwe also has significant chrysotile asbestos production. Amongst the amphibole asbestos minerals crocidolite (mainly mined in South Africa and Australia) and amosite (mainly mined in South Africa) are no longer produced, but active mining of anthophyllite asbestos and tremolite asbestos still occurs, for example, in India.[9–11]

Since the acceptance of the toxic properties of asbestos, asbestos products have often either been banned (European Union) or at least become very much less common (USA). Concern over asbestos exposure in the workplace is waning in these regions, although there is still the problem of encountering and disturbing asbestos previously used for insulation and in construction materials, for example in ceiling and floor tiles, wallboard, cement pipes, fillers (spackle and grout) and mastic.[12] Greater concentrations of asbestos-contaminated materials can be found at sites of past production and use of asbestos products. However, at least in the developed world, these legacy problems are the focus of relatively intense clean-up operations once identified. When considering the dangers of asbestos, whether in use, or through past exploitation and use, or simply because it is a naturally-occurring mineral, it must be kept in mind that lung cancer can have many triggers, and that even mesothelioma has other causes, albeit rare, besides asbestos exposure.[13]

Naturally occurring asbestos

A new concern has arisen over asbestos being a naturally occurring constituent of rocks and soils. The presence and concentration of asbestos in rocks is controlled by the geologic history and it is possible to predict areas where there is a potential for significant quantities of asbestos to occur in rocks or the soils derived from them.[14] The presence of asbestos combined with pathways of exposure can lead to a significant hazard that may lead in turn to increased risk of disease. This is known as naturally occurring asbestos (NOA), although what is referred to as NOA may include materials that do not fit some of the current industry or regulatory definitions of asbestos. It is also not clear that all forms of NOA present the same risk as commercially exploited asbestos.

It is well-known that miners engaged in extracting and processing asbestos are at serious risk of disease, as are those workers that produce the finished goods. This risk is shared by their families due to take-home contamination and also by those living in the community around the sites of extraction or production. Pollution from these activities ensures a hazard will exist for many more years in some of these areas.[15] In the mining regions, it is obviously difficult to separate out the potential for exposure and disease from the simple presence of asbestos in the soils and rocks in the absence of mining activities. In South Africa the early identification of mesothelioma associated with asbestos mining was based on cases drawn predominantly from outside the workplace. In addition, studies of non-occupationally exposed community residents (*e.g.* white women) also showed elevated disease risks.[16] It is estimated that 23% of mesothelioma cases in South Africa are a result of environmental exposure to asbestos.[17] However, at the time these exposures occurred, asbestos mining was in full swing, and community exposures were exacerbated by the use of mine tailings for many purposes, including road surfacing and making bricks and plaster, and also by the presence of waste dumps or tips on which children played. Thus, it is probably not now possible in these localities to deduce a community risk in the absence of asbestos mining activities. A similar picture has been identified in the crocidolite mining region of Australia.[18] In a study of 726 cases of mesothelioma in Western Australia, 43 cases (6%) had environmental exposure only, but only in six (less than 1%) was the exposure considered due only to residence in an asbestos mining region. Asbestos was never commercially mined at the vermiculite mine in Libby, Montana, but the ore contained very large quantities of fibrous amphiboles.[19] In a study to examine the health problems of miners and residents there was found to be a 6% incidence of radiographic evidence of asbestos-related disease in residents with no known occupational or familial exposure.[20] However, the risk of disease from simple residence in Libby has been argued to be small to negligible.[21] There are also several areas outside of the USA where large-scale mining of asbestos has never occurred, but where the inhabitants have been shown to be exposed to fibrous minerals (asbestos or otherwise) and at risk for disease. In many cases, what have been reported were pleural plaques and this has not been associated with an excess of mesotheliomas in every case.[22] Such reports have come from many different regions of the world, and have involved a number of different minerals, not all of which fall within the traditional definition of asbestos. The regions and minerals include: Turkey (tremolite and erionite), Greece (tremolite), Cyprus (chrysotile and tremolite), Austria (tremolite), Corsica (tremolite and chrysotile), Afghanistan (tremolite), Sicily (fluoro-edenite), New Caledonia (tremolite), China (crocidolite), Japan (anthophyllite, tremolite and chrysotile), Bulgaria (anthophyllite, tremolite and sepiolite) and Finland (anthophyllite).[23–37] In addition to the mining regions of South Africa and Australia, environmental-only asbestos exposure may also occur in mining regions of Italy.[38] Where asbestos has not been mined, the exposure pathway may have been through the quarrying of some other stone, and in many cases it has been through the use of natural soil as 'whitewash' for buildings. However, there does appear to be at least a possibility that more common activities such as digging soil may lead to significant exposures and associated health risk. In Bulgaria, pleural plaques were found in tobacco farmers whose soil contained mineral fibers, but where there was little asbestos mining, and that took place underground.[36] In a study of goats in Corsica,[39] and a more recent study of pets from El Dorado Co., California,[40] asbestos fibers have been found in the lungs of animals. A recent study of mesothelioma records from the cancer registry in California indicated the closer one lived to ultramafic rock formations (one of the host environments for NOA) the higher the risk of mesothelioma, after adjustment for sex, age and occupation, while no similar correlation was found for pancreatic cancer, which has no relationship to asbestos exposure.[41] However, this study may be criticized in several aspects, for example in failing to account for migration (both immigration and emigration are common). Thus it is arguable whether a relationship between living in an area with naturally occurring fibrous minerals in soil and asbestos-related disease (lung cancer or mesothelioma) has been firmly established. The highest probability of risk will be related to soil disturbance through farming and construction (and deposition and re-entrainment), but some recreational activities will also disturb soil and lead to airborne dust.

Libby amphibole and other minerals

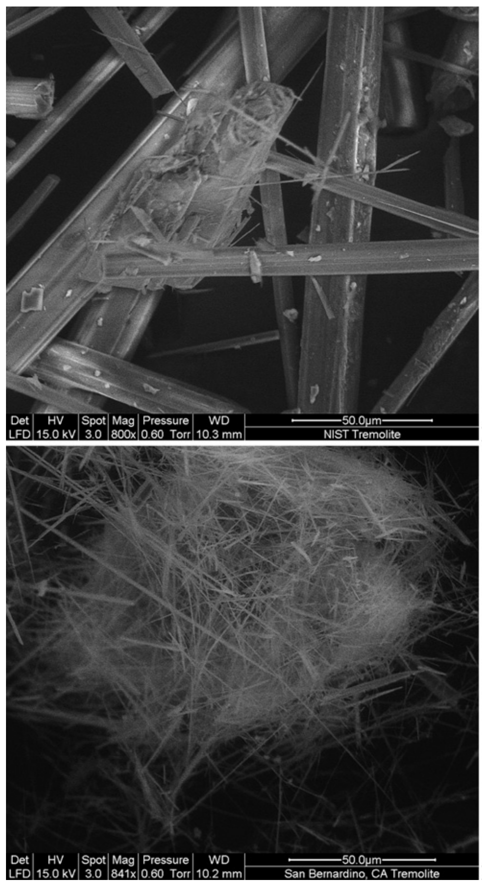
In the USA, a great deal of attention has been focused on the natural occurrence of asbestos through the outbreak of disease at the vermiculite mine located near Libby, MT. The vermiculite ore is heavily contaminated with fibrous amphiboles, including tremolite asbestos. The other amphiboles (winchite and richterite) are also asbestiform, *i.e.* they have crystallized in very long and thin fibers in a parallel orientation, the habit of the minerals recognized as asbestos.[42] Since 1978, amphibole minerals have been classified according to chemical composition.[43] However, the classification has to take into account variations in composition due to the phenomenon of solid solution, which is common in many silicate minerals. Sites in the silicate lattice which are occupied by cations are fairly large, and can accommodate cations in a range of sizes, so the electrical balance can be satisfied by approximately similarly sized cations of the same valence state. Thus Na^+ can be replaced by K^+, or Mg^{2+} by Fe^{2+}. In some cases, cations can also be replaced by cations of a different valence state if the ionic size is similar, and thus, for example, Na^+ can be replaced by Ca^{2+}. Where complete replacement occurs, it is easy to identify and classify these 'end-member' minerals. Partial replacements may cluster around preferred proportions, which may assist recognition and nomenclature. In many cases, however, purely artificial boundaries of composition have been used to classify minerals. As the content of sodium increases in tremolite it becomes winchite, and with potassium, richterite, but the exact divisions are a human invention and do not appear to reflect any natural division at Libby, where the range of compositions of analysed specimens encompasses all three fields. Thus, within an expanded mineralogical definition, all of the amphibole mineral at Libby could be considered a single mineral, and if that were to be termed tremolite, all the asbestiform mineral would be classified as tremolite asbestos. Meeker has pointed out that all of the Libby amphibole would have been correctly referred to as sodium-rich tremolite using the non-chemical definitions in place prior to 1978.[44] Mineralogical definitions have certainly changed over time and might do so again,[45] but such changes are rarely reflected in legal definition in the short term. Thus a large proportion of the asbestiform amphibole at Libby was not considered asbestos by a U.S. Federal Court decision in 2006,[46] but this was overturned after the U.S. Government appealed the decision to the 9th Circuit Court of Appeals in 2007.[47]

Much of the amphibole in the vermiculite ore at Libby was liberated during processing (which led to the exposures of workers, their families and other residents).[48] However, sufficient amphibole remained (0.3–7%) in the ore shipped to exfoliation plants around the U.S. to raise concerns over contamination of the many sites where the vermiculite was expanded into the ‘zonolite’ product.[49] Zonolite was principally used for insulation, and is found loose in the attics of many homes in the USA. Research has shown the potential for disturbance of zonolite insulation in such confined spaces to lead to airborne fiber concentrations of concern.[50] Advice on dealing with this situation is available.[51]

The fluoro-edenite suggested as the hazardous mineral in Sicily is also an asbestiform amphibole although not strictly speaking asbestos.[52] Other fibrous minerals unrelated to amphiboles may also be hazardous. Balangeroite is a fibrous mineral contaminant of chrysotile from Balangero, Italy, that is similar in toxicology to fibrous amphiboles.[53] While the most common asbestiform variety of the serpentine family is chrysotile, asbestiform antigorite has been noted from Poland, New Caledonia and Australia.[54–56] Fibrous erionite, a member of the zeolite family of minerals, which is considered to be a cause of disease in Cappadocia, Turkey[57] is considered to be as hazardous as crocidolite (asbestos).[58] It can be found in North Dakota (www.health.state.nd.us/EHS/Erionite). Another fibrous zeolite is mordenite, which while less active than erionite, may still cause fibrosis.[59] The possible risks from fibrous zeolites has prompted an evaluation of their occurrence in the USA.[60] Palygorskite, a fibrous clay mineral is considered toxic[61] and is listed as a carcinogen on the State of California registry[62] when fibers are longer than 5 μm. Industry has often referred to palygorskite as ‘attapulgite’, from the locality at Attapulgus, Georgia, USA. ‘Attapulgite’ is not a mineral name, but has been retained by industry as a tradename to refer to non-fibrous palygorskite.[63] There is some controversy as to whether attapulgite, *e.g.* from Mormoiron, France, is as toxic as fibrous palygorskite.[64] An epidemiological study of workers that had been employed in the mining and milling of attapulgite from Attapulgus found an excess of cancers in Caucasian male workers, but a deficit amongst non-white males.[65] Non-malignant respiratory disease was reduced in both groups of workers even though total dust levels could be high.[66] Sepiolite, another clay mineral also can present a fibrous habit. It is well-known as the source material for meerschaum. In animal experiments it has been shown to be fibrogenic but not always carcinogenic.[59] Sepiolite workers in Turkey showed fibrosis, but not associated with exposure.[67] Fibrous brucite, on the other hand, is considered both fibrogenic and carcinogenic.[59] Wollastonite, which occurs as crystals described as acicular and sometimes as fibrous also has been considered for potential risks, but it is not considered carcinogenic.[68] Fibrous talc is another mineral for which there has been some concern and some controversy, which will not be detailed here. Suffice it to say that the composition of talc is related to that of amphibole and it can evolve through metamorphism of amphibole minerals. Thus it can often be found either alongside or grading into asbestiform amphibole.[69] While carcinogenicity of the pure material has been debated, there is no dispute that excessive exposure can be fibrogenic.[70,71] However, this is not likely to be an issue for low-level, environmental exposures.

Prismatic amphibole crystals and cleavage fragments

The asbestos habit is characterized by a finely filamentous parallel crystal growth along a preferred axis, accompanied by multiple twinning and the presence of chain width disorder planes.[72] This complexity results in asbestos of varying grades, *i.e.* fibers of varying width and length. In Fig. 1, two electron micrographs of different specimens of tremolite asbestos are shown, both of which are considered Standard Reference Materials. The difference in the dimensions of individual fine fibers (known as ‘fibrils’) is clear. In addition to crystallizing in the asbestiform habit, the same amphibole minerals can also crystallize in more massive forms, that may be termed fibrous or acicular or prismatic, or as even larger masses.[73] For example, in the Pike’s Peak district of Colorado, famous for many different types of large crystal forms, the same chemistry found in crocidolite crystallizes as riebeckite, in crystals many millimetres in diameter and many centimetres long (Fig. 2). While riebeckite is a relatively rare mineral, the non-asbestos forms of tremolite and actinolite are very common, as are the non-asbestos forms of amosite, known as cummingtonite or grunerite according to the composition.



1a

1b

Fig. 1 Two standard tremolite asbestos materials photographed under Transmission Electron Microscopy at 800×. Source of materials: (a) Research Triangle Institute, Research Triangle Park, NC, USA (representing the source material for the National Institute for Standards and Technology Standard Reference Material), (b) Health and Safety Executive, United Kingdom. Photographs courtesy Research Triangle Institute.

Fig. 2 Riebeckite crystals. St. Peter's Dome, Colorado, USA, collected by the author.

Byssolite is a term that was originally used to define a stiff, fibrous form of actinolite, which grows as single twinned fibers into a matted mass, rather than as bundles.[73] Individual fibers were described as thick and quite brittle, and lacking the fibrillar structure or high tensile strength of asbestos. However, the Commission of New Minerals Nomenclature and Classification (CNMNC) of the International Mineralogical Association (IMA) prefers that different habits of the same mineral are not named differently and so this nomenclature has been discredited.[74] Fine, prismatic crystals, while not usually as fine as individual asbestos fibrils, may be mistaken for bundles of fibrils. In addition larger crystals can break, usually along preferred planes of cleavage. Such 'cleavage fragments' may also be long and thin and resemble individual asbestos fibrils or bundles of fibrils.[73] Exploitation of practically any rock containing amphibole minerals (and, occasionally, the serpentine minerals) is likely to lead to airborne cleavage fragments that will be seen as potentially asbestos under the phase-contrast light microscopy (PCM) traditionally used for assessing fiber concentrations.[75] Regarding these particles as fibers in the same category as asbestos fibers may or may not be appropriate. These particles of respirable dimensions can be inhaled. However, the toxicity of inhaled non-asbestos mineral cleavage fragments or prismatic crystals is highly contentious. For example, in the USA, the National Institute for Occupational Safety and Health (NIOSH) has expressed an opinion in testimony both to the Occupational Safety and Health Administration (OSHA)[76] and the Mine Safety and Health Administration[77] hearings on asbestos regulation that (a) there is a similarity in size, shape and composition between these types of particles, and (b) the evidence for an absence of toxicity for non-asbestiform amphibole particles that meet dimensional criteria for an airborne fiber is equivocal. Thus NIOSH concluded there is no scientifically valid reason to exclude cleavage fragments from regulation, and doing so may compromise the protection of workers exposed to mixed fibers. Nevertheless, fibers that are not derived from specific asbestiform amphiboles are not currently covered in the US occupational regulations. The U.S. Environmental Protection Agency (EPA), however, has taken a position that "it is prudent at this time to conclude equivalent potency [of cleavage fragments and fibers] for cancer".[78] It is not easy to distinguish cleavage fragments from asbestiform fibers in routine PCM analyses, although it may be possible to use dimensional criteria applied to a large population of fibers objects in a sample.[79] This may not work as well if the population is mixed, and there may be insufficient particles collected on which to perform the necessary statistics. Currently, the American Society for Testing and Materials (ASTM International) has a procedure purporting to distinguish the two, which is currently being tested.[80–82]

Naturally occurring asbestos in the USA

The presence of asbestos or asbestiform minerals in rocks is now well-known.[83] The geological conditions necessary for the formation of NOA have been reviewed and the rock types known to host NOA include serpentinites, altered ultramafic and some mafic rocks, dolomitic marbles and metamorphosed dolostones, metamorphosed iron formations, and alkalic intrusions and carbonatites.[84] There have been many asbestos mines and prospects for mines throughout the USA, and many other reports of asbestos or other fibrous minerals from geological surveys. The United States Geological Survey (USGS) is compiling these sites and locating them on maps that are available on its web-site. The first four of these maps covering the Eastern USA (Fig. 3),[85] the Mid-West,[86] the Rocky Mountains[87] and the South-West[88] have been published, and a further map, covering the Western States, is expected in 2009. The sites on these maps give an indication of the major areas of concern, which are most particularly located along the Appalachian Mountains, and also in the Western Cordillera. Concern has already been expressed in some of these areas, for example in Virginia and California, where asbestos is a very common component of the local geology. The local response to the discovery of NOA has been quite different in these different areas. While health concerns are obviously a factor in the response, the effect on property values of NOA can be quite dramatic, and sometimes disproportionate to the health risk. An escalating concern can be driven by media attention. Experts may come to differing conclusions from the same evidence. This may serve to allay or inflame concerns. Perceived or actual bias may be charged. Litigation may be involved. The outcomes are not always rooted in purely scientific considerations.

The health risks are based on the potential for exposure. The exposure pathway of greatest concern is through inhalation, which requires the asbestos to become airborne. It is unlikely that simple wind erosion would lead to severe exposures. In general, there would need to be physical disturbance of the soil under dry conditions. Thus health risks are normally assessed through 'activity-based' sampling, which involves taking personal air samples for professionals engaged in typical local activities that have potential to aerosolize soil or settled dust. This has led to some quite engaging, though very serious, photographs of researchers dressed in protective gear, including respirators, playing soccer (Fig. 4), basketball and baseball (sliding to base),

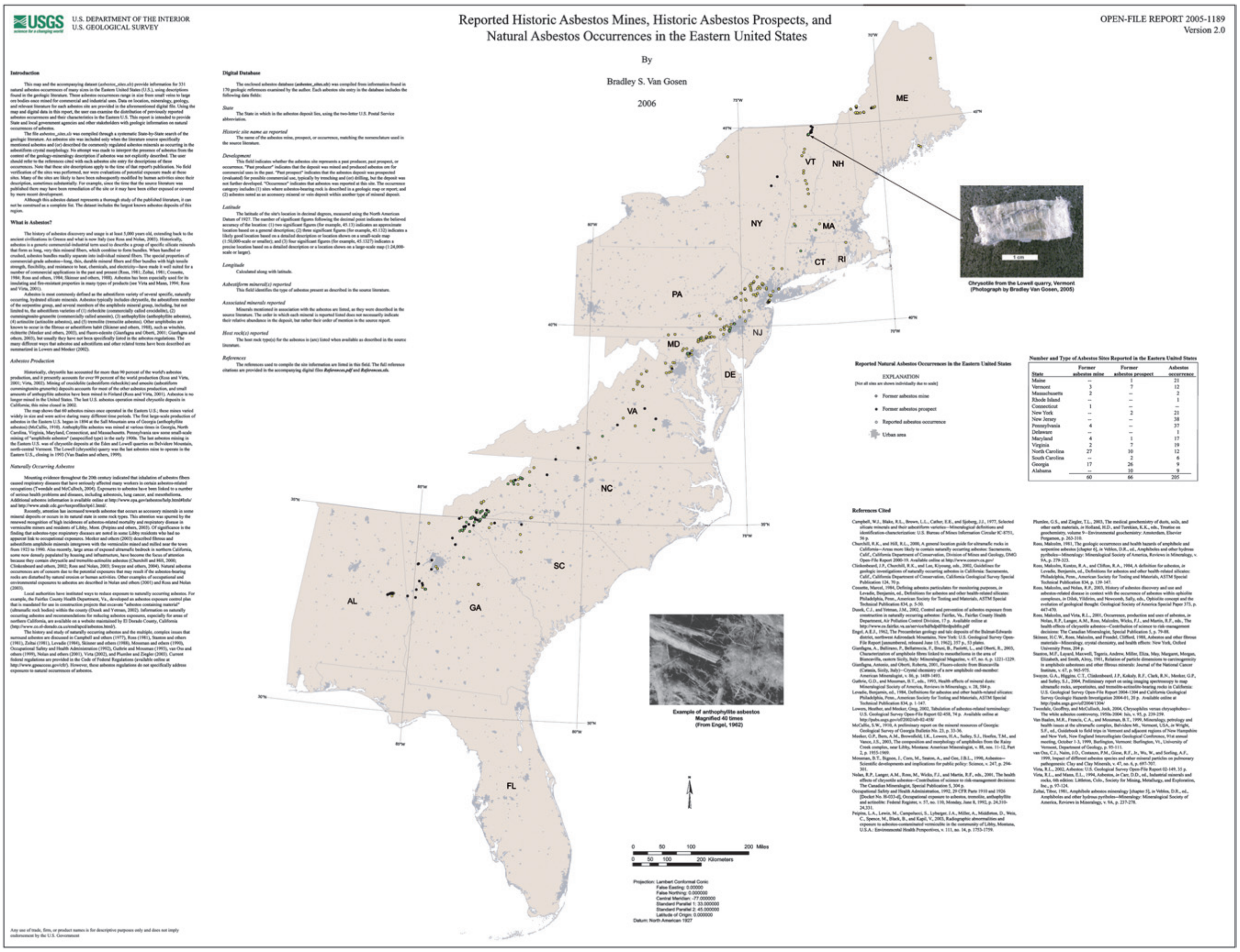


Fig. 3 United States Geological Survey map of asbestos occurrences in the Eastern USA.

Fig. 4 Activity sampling: playing soccer. Photograph courtesy US Environmental Protection Agency.

Fig. 5 Activity sampling: bicycle riding. Photograph courtesy US Environmental Protection Agency.

riding bicycles (Fig. 5) driving all-terrain vehicles, *etc.* In one investigation of asbestos products washed up on a beach (Illinois Beach State Park) it was even thought appropriate to build sand-castles![89]

Many of the locations detailed below have been the subject of investigation by the Centers for Disease Control, Agency for Toxic Substances and Disease Registry (ATSDR) and/or the EPA.

Fairfax County, Virginia

Around 20 years ago asbestos was discovered in the soils of Fairfax County, VA, which includes part of the metropolitan and suburban area of Washington, DC.[90] Approximately 11 square miles of the county, including a part of Fairfax City has been mapped as containing asbestos formations in greenstone underlying the Orange Soils Group. Surface exposure of the rock formation is rare. The county has published local maps indicating areas with geology of concern, as well as much information regarding the hazard and protocols for exposure control during construction in those areas.[91] Before beginning any construction activities, a compliance plan must be submitted and reviewed by the Fairfax County Health Department. The purpose of a compliance plan is to maintain safe working conditions on the construction site and prevent migration of asbestos laden dust off the site. The compliance plan includes directives on performance and monitoring.[92] Advice on personal protective equipment is also available.[93] Over freshly developed sites, contractors are required to lay 6 inches (150 mm) of clean, stable material over the ground. Since the response to NOA has caused little major disruption to this community, it might be considered a model for other local communities dealing with NOA.

El Dorado Hills, California

El Dorado Hills, in the Sierra foothills near Sacramento, CA is a community that appears to be having a more difficult time struggling to adapt to the presence of fibrous amphibole in the bedrock and soils. Research assessing the risks of living in this community has shown, for example, the possibility of airborne fiber concentrations of concern through almost any disturbance of the soil, for example while gardening or in parks while playing baseball.[94] The presence of NOA has even led to homeowners abandoning their property.[83] Without doubt, there has been much more media attention focused on this situation, and this has in part been fueled by an explosive growth in population from around 12 000 in 1991 to 31 000 at the beginning of 2005.[95] The presence of NOA has been an issue since at least 1999, but in February 2002, construction of two soccer fields began at a local school. During construction, veins of asbestos-bearing minerals were disturbed. The School District reportedly encountered difficulties in acquiring reclaimed irrigation water for the project, so the soccer fields were left without landscaping for more than a year while a solution was sought. Subsequent erosion of disturbed, potentially asbestos-bearing soils from the unfinished fields caused by winter rains in 2002 and 2003 impacted classrooms and locker rooms downslope. The school soil was remediated that summer, but in September 2003, the EPA received a petition under the Superfund Law (also known as CERCLA, which stands for the Comprehensive Environmental Response Compensation and Liability Act) to assess asbestos exposure at public areas near the school. EPA contractors collected samples at a community park (including a nature trail), three schools and at an unpaved parking lot. During this investigation, activity-based sampling involved measuring NOA in the breathing zone during simulated baseball, basketball and soccer games at the schools and park, running and biking on the trail, playing in the children's playground at the park, and gardening at a school garden. Samples were analysed both for the long fibers regulated in workplaces and used in EPA risk assessments and also for the short fibers which are included in regulations governing schools. Fibers were found in nearly all samples.

In this particular case, there has been some debate about the nature of the NOA. Initial studies by the EPA indicated the presence of actinolite fibers. This was criticized in a report from a commercial laboratory, which concluded (among other items) that the composition of this mineral was not compatible with asbestos formation, that the optical properties were inconsistent with asbestos and that the form (aspect ratio) of the fibers was consistent with cleavage fragments.[96] The EPA supplied a rebuttal to the report, which included their position that they did not discriminate between asbestos fibers and cleavage fragments.[97] Most recently, extensive research by the USGS has identified the mineralogy of these fibers to be mostly weathered, prismatic to acicular single crystals of actinolite-magnesiohornblende which match the dimensions of crystals *in situ* in the country rock, and which also meet the dimensions and chemical composition of fibers as regulated by the EPA, together with tremolite that is fibrous and grades towards asbestiform.[98] Some chrysotile fibers were also found which were not disputed. There is a possibility that these may have come from soils added to those already at the baseball field and children's playground. Other parts of El Dorado Co., such as Garden Valley, have chrysotile NOA.

The EPA and ATSDR have held meetings and have produced fact sheets to inform the public of their findings and to explain the risks. In order to keep the risk of asbestos exposure at a minimum, the State of California Air Resources Board (CARB) and El Dorado County's Air Quality Management Division enforce a number of regulations designed to significantly decrease the chances that asbestos in soil and rock can become airborne, and thus minimize NOA dust. To begin with, owners and operators are required to notify the local air quality management district within one business day of discovering NOA, serpentine mineral, or ultramafic rock in an area to be disturbed by construction, grading, quarrying, or surface mining operations. These regulations do not prohibit construction activities, but in locations where NOA can be found, construction projects must have dust-control measures in place as well as mitigation procedures for soil and rock areas disturbed by construction.[99] In addition, the asbestos ordinance also requires a disclosure as part of real estate transactions for properties where NOA soils are known to have been disturbed. CARB also has regulations controlling the use of materials containing NOA for surfacing.[100] The California EPA Department of Toxic Substances Control with US EPA funding conducted an assessment in El Dorado County of emissions from roads paved with serpentine gravel[101] and has recommended that serpentine gravel roads throughout California be re-surfaced to eliminate mineral fiber (mainly chrysotile) emissions.[102]

Clear Creek management area, California

The official state rock of California is serpentine, the source of much of the NOA in California. Areas with potential NOA can thus be found throughout the state and guidelines for assessing the presence of NOA have been published.[103] The Clear Creek Management Area (CCMA) in San Benito and Fresno Counties is a recreational area south of Sacramento, CA, which is also the subject of EPA investigations.[104] The rugged terrain is a popular and challenging riding spot for off-road motorcyclists. The naturally barren slopes, bald ridges, chaparral and rare plants are also enjoyed by rock collectors, botanists, hikers, hunters and campers, including families with children. Thousands of visitors each year use hundreds of miles of criss-crossing routes left by mining activities (*e.g.* the New Idria mercury mine). It is located on 31 000 acres of serpentine containing chrysotile, which also was commercially mined (Coalinga and Atlas Asbestos Mines). Although the mine has been cleaned up under the Superfund legislation, concern remains over NOA outside of the mine boundary. The CCMA is managed by the Department of the Interior's Bureau of Land Management (BLM). BLM has designated the area as hazardous, and warning signs are posted at entry points and on bulletin boards. Results of activity-based sampling in 2004 showed extremely high fiber exposures for drivers of motorcycles and sport-utility vehicles, particularly when riding behind the lead vehicle. Certain areas of the CCMA are now closed to motorized vehicles during the dry season,[105] which has led to a backlash from some recreational users.[106] The backlash is based in part on reports that the chrysotile in this deposit (known as Calidria or Coalinga chrysotile) is a 'short-fiber' asbestos with no amphibole contamination (at least in the mined area), and which is even less biopersistent than other chrysotile varieties, so that it therefore carries considerably lesser risk than other asbestos materials.[107] Although the asbestos is often referred to as 'short-fiber', this likely refers to the commercial nature of the asbestos, and probably has little bearing on the sizes of airborne asbestos fibers. The US EPA has just released its risk assessment for CCMA indicating a lifetime risk for lung cancer above acceptable levels associated with even a single day per year of vehicular activity in the area.[108] Children were considered to be at greater risk. The risk assessment was based only on 'long' fibers exceeding 5 μm in length. In addition, 8% of the fibers collected in the EPA air samples were considered amphibole (tremolite, actinolite or other), rather than chrysotile. This is reasonable considering that a deposit of this size may have substantial variations in mineralogy across the deposit and that the mined area may not be representative of the whole.

Silver Bay, Minnesota

Taconite is a metamorphic iron-ore found in the north-central USA around Lake Superior and Lake Michigan.[109] The ore mineral is the iron oxide, magnetite, while gangue minerals include amphiboles, most particularly developed where the ore body abuts a local igneous intrusions called the Duluth gabbro in north-eastern Minnesota. The closest ore working to the Duluth gabbro is now closed, the next nearest being the Peter Mitchell pit, whose ore is processed at a facility on the lake shore. Much has recently been published on the geology of the formation and specific mineralogy of the Peter Mitchell pit as a result of an International Symposium on the Health Hazard Evaluation of Fibrous Particles Associated with Taconite and the Adjacent Duluth Complex (St. Paul, MN, 2003). Amphiboles in this pit are from the cummingtonite-grunerite and actinolite-ferroactinolite series.[110] They can be found as individual fine prismatic crystals or in fibrous bunches. Extracting iron from the taconite ore is a challenge that was only mastered in the 1940s. The very fine-grained magnetite is released from the other carbonate and silicate minerals by extensive grinding of the ore and this is followed by magnetic separation. The fine magnetite grains are then mixed with binders and roasted to form pellets, while the gangue minerals are slurried and removed for disposal. Locating the processing mill, at Silver Bay on the shore of Lake Superior provided a steady supply of water for the production process as well as a harbor for refined ore shipments. The lake also formed a convenient dump site for the tailings in the early days of operation. Unfortunately, this resulted in mineral fibers appearing in the water supplies of other shore towns including the city of Duluth, MN. Mineral fibers were also found in the air of Silver Bay. At the time, the mining company was called Reserve Mining, and the resulting legal battles were so ground-breaking, they are often referred to as the Reserve Mining case.[111] In 1974, a Federal District Court judge (Judge Lord) ordered the company to cease discharging tailings into the lake. The company survived an immediate shut-down by appealing for time to develop a land-based disposal system.

Initial complaints against the company were based on macroscopic effects on the lake and its fauna. However, when microscopic mineral fibers were detected in the air and water supplies, the issue of toxicity became paramount. The closure order of 1974 cited a 'substantial' danger to human health. There was considerable debate over whether the amphibole fibers found were asbestos, as well as whether ingestion, as compared to inhalation, of the fibers could lead to disease. The US EPA later set a drinking water goal of 7 million asbestos fibers >10 μm long per litre based on increased risk of developing benign intestinal polyps.[112]

Most of the fibers found were short, generally shorter than the 5 μm minimum length used in several regulations on asbestos. However, some experts argued that risks may be posed by these short fibers, prompting a dispute which has carried forward to today (much of the mineral fiber found in dusts from the World Trade Center disaster was <5 μm long). The fibers from the taconite mill were claimed by the company to be cleavage fragments rather than asbestos fibers.[111] A recent investigation of the geology of the Peter Mitchell pit found no asbestos *per se* in the ore, but did find a few fibrous bundles of amphibole minerals, some of which has been altered to sepiolite (note: this author has also found fibrous ferroactinolite at this particular pit).[110] It is unlikely that these fibrous minerals contribute as much to airborne fibers as do the cleavage fragments of the more common coarsely crystalline grunerite-cummingtonite.[113] Current controversy concerns a reportedly higher than expected rate for mesothelioma in male residents in the counties including the Minnesota taconite area, many of whom would have worked in taconite extraction and processing.[114] However, for the initial set of cases, possible exposure to asbestos could also be found in the case histories,[115] although this was most likely exposure to chrysotile, which is thought to present a lower risk of mesothelioma than does exposure to amphibole asbestos (the minerals in the Peter Mitchell pit are amphiboles). The number of cases has risen to 58 since this investigation, still all male and all with a history of working in taconite.[116] Interestingly, the cases had worked in pits variously located along the taconite outcrop, not just at the eastern end, and this might indicate a risk from exposure to other fibrous minerals known to occur at the western end, such as minnesotaite (iron-rich talc), greenalite (iron serpentine) and stilpnomelane (a sheet silicate).[109] It may be significant that workers were also exposed to silica dust.

The finding of excess mesothelioma has caused some renewed interest in the airborne emissions from the plant, which could not be rendered completely free of mineral fiber particles.[117] In the absence of a 'safe' level for mineral fibers, in 1975 the 8th Circuit Court of Appeals instituted what is known as the 'control-city' standard, which provided that air monitoring at Silver Bay should not result in concentrations exceeding those in a control city, in this case, St. Paul, MN. In both communities fiber levels have dropped by an order of magnitude since that time, but the levels in St. Paul have dropped slightly faster (presumably due to the decrease in chrysotile use, for example, in brake-linings). The situation of a ten-fold reduction in emissions being considered less acceptable than the status quo thirty years ago is not without precedent in the history of toxicology, but the fact that the situation is not based on results from toxicity studies may be considered unusual if not unprecedented. A petition by the company to clarify the control city ruling was denied by the federal appeals court and the matter was remanded to state court for settlement. In 2008, the state approved a significant appropriation of funds to the University of Minnesota to investigate the mesothelioma issue. In addition to being a source of iron, 'Mesabi hard rock' has had over 400 other documented uses, including over 1000 miles of roadway pavement or fill. An insightful publication dealing with the 'Reserve Mining Controversy' describes well how even unequivocal scientific 'facts' do not necessarily lead to unequivocal policy conclusions, and reflects on how very tortuous policy development becomes when the 'facts' are open to multiple interpretations.[118] The Reserve Mining Controversy illustrates how divergent values and ethics also become embroiled and this theme is the subject of a comment from Robert Sheran, counsel for the company and later Chief Justice of the Minnesota Supreme Court, to Judge Lord 'that a lawsuit is not the best place in the world to develop scientific conclusions, and that the advocacy process, necessary though it may be, sometimes causes parties to litigation to assert positions that may have an impact on the legislation, to be sure, but which, absent the lawsuit, they would never assert in a responsible way'. It may be noted that Judge Lord was removed from the case in 1976 for exhibiting advocacy in place of impartiality.[118] A review of the history of this case can not provide direct solutions for the issue of NOA, but can provide ample lessons in dealing generally with environmental issues and controversies.

Sparta, New Jersey

Asbestos is common in New Jersey, especially in the Pre-Cambrian marbles and limestones.[119] Lime Crest Quarry (which has also been known as Southdown Quarry, and Cemex Quarry) is a marble and limestone quarry near Sparta, NJ. A development known as Sussex Mills has grown up close to the quarry and has been the source of complaints regarding the presence of possibly fibrous tremolite in dust emitted from the quarry operations, such as lime roasting.[120] As with most amphibole occurrences, there is little doubt about the chemical composition of the mineral, but controversy over the mineral habit. The State of New Jersey required the quarry owners to test emissions from the quarry and tremolite was reported. The tremolite was later stated to be non-asbestiform. The state attempted to shut down the quarry in 2000 citing general emissions (not asbestos specifically) but this was not accepted by the court, which ordered the state and quarry owners to reach a compromise. A contractor for the state collected samples indoors and outdoors of residential homes located close to the quarry in 2002.[121] No asbestos structures were found in indoor air samples and only occasional structures were found in samples from outdoors. Two settled dust samples from indoors were found to contain asbestos structures but this appeared to be more related to the age of the homes than to their proximity to the quarry. The asbestos was considered to be chrysotile and tremolite. Controversy arose over the use of an asbestos definition that has been proposed to the US EPA but which has not been accepted by them. This definition only includes fibers thinner than 1 μm as asbestos.[122,123] The issue of the health effects of the emissions also split the town, since the quarry is a large local employer. The owners at that time (a company headquartered outside of the USA) have since sold the quarry to a local developer, but it is still active. Just over the state line in the town of Warwick, New York sits a similar quarry shut-down in 1983 that might re-open.

Ambler, Alaska

Ambler is located on the bank of the Kobuk River in the Brooks Range of northern Alaska. The geology around Ambler has resulted in economic potential for copper and gold, but also for asbestos and the related mineral, jade (nephrite). The commercially exploitable asbestos is chrysotile or tremolite, found in serpentinites, particularly around the aptly named Asbestos Mountain.[124] However, the asbestos was not thought to be of good quality, but rather was considered to have an unusually high dust or fines content. In 2003, the Alaska Department of Transportation (ADOT) was conducting routine testing of borrow material soils in Ambler, in preparation for a scheduled project. ('Borrow material' is a construction term for soil or rock removed from a 'borrow pit' and used in construction elsewhere.) Routine tests revealed the presence of chrysotile in the soil samples taken from the local pit, which is commercially owned by a local development corporation.[125] The local development corporation promptly closed the pit[126] and several projects, including completion of a sewage treatment plant scheduled for 2006, have since been held up pending the development of alternative aggregate sources.[127] The State Department of Environmental Conservation was contacted with regard to air sampling, and later the ATSDR became involved. The borrow soil has been used to create unpaved gravel road surfaces, where all-terrain vehicles (ATVs, the powered vehicle of choice in this remote region) can raise substantial quantities of dust containing chrysotile in dry weather. At the request of the Tribal Environmental Department of the Maniilaq Association, ATSDR performed an exposure investigation to determine if riding ATVs on gravel roads lead to significant asbestos exposures for riders and pedestrians along the side of the road.[128] Recommendations to reduce dust include lowering speed limits and watering roads. Ambler is included in the EPA's asbestos project plans.[129]

Swift Creek, Washington

On Sumas Mountain in western Washington State a major slow-moving landslide is occurring in altered serpentinite rock near the headwaters of Swift Creek. The slip material contains both 'asbestiform and non-asbestiform lizardite' (lizardite is a serpentine mineral not normally thought to occur in an asbestiform habit, so presumably chrysotile is the asbestiform mineral referred to here).[130] Erosion releases 120 000 cubic yards of sediment into the drainage each year. This has led to redeposition of asbestos in gravel banks in rural residential and agricultural areas down river. This material is dredged from the river to control flooding. The dredge piles along the sides of the river have become a local source of fill, and also form an area used for recreational activities. In 2006, the US EPA engaged in activity-based sampling. Three activities involving different levels of disturbance of the dredged material were simulated for this study: loading and unloading of dredged material with heavy equipment, shoveling and raking dredged material over a surface, and recreational activity on the dredged materials (mountain biking, jogging, and walking).[131] Even though the majority of the chrysotile fibers were shorter than the 5 μm minimum length for fibers regulated in the workplace, there remained sufficient longer airborne fibers during some of the activities to indicate a potential for exceeding the legal limit for workplace concentrations in the US. Stationary, non-personal samples generally gave results an order of magnitude lower. In 2007, the US EPA released a fact sheet warning residents to limit their exposures through avoiding contact with the dredged materials.[132]

Quantifying asbestos in air and soil

A review on NOA would not be complete without reference to the methods for measuring asbestos in air and soil. Air monitoring was first adopted as part of the attempt to control occupational disease, and thus we have methods promulgated by government agencies such as NIOSH (Method 7400),[133] OSHA (Method ID-160),[134] and the Health and Safety Executive in the UK (MDHS 39/4),[135] as well as by other government agencies in Europe and Russia. In addition, methods have also been promulgated by the Asbestos International Association,[136] ASTM International (D7201-06),[137] the World Health Organisation[138] and the International Organization for Standardization (ISO 8672).[139] All of these methods use PCM as it is simpler, quicker and cheaper than electron microscopy and it can be carried out in the field, and thus this procedure has also been adopted for use in the environmental arena. As noted, PCM may not adequately be able to distinguish true asbestiform fibers from prismatic single crystals or cleavage fragments. Many practitioners prefer electron microscopy, generally transmission electron microscopy (TEM), because of its higher magnification and better resolution, as well as the possibility of gaining further information about the nature of the particle, including chemical and crystallographic structure, to aid in identification. However, even with TEM it may not be possible to adequately distinguish asbestiform fibers from prismatic crystals and cleavage fragments. Example methods are NIOSH 7402,[140] ASTM D6281[141] and ISO 10312.[142] There remains controversy, however, as to which method and which counting rules to use. For example, the Asbestos Hazard Emergency Response Act (AHERA) requires the counting of any asbestos 'structure' longer than 0.5 μm (with an aspect ratio $> 5 : 1$),[143] while most other methods restrict counts to particles longer than 5 μm. In addition, various aspect ratios have been used to describe fibers, including 3 : 1, 5 : 1, 10 : 1, *etc.* Some methods restrict counts to fibers < 3 μm width, as this is supposed to represent those particles most likely to penetrate deep into the respiratory tract. PCM is restricted by resolution to widths somewhere in the range of 0.05 to 0.25 μm, depending on the quality of the optics, the set-up of the microscope, the difference in refractive index between the fiber and the mounting medium and the visual acuity of the microscopist.[144] Very much finer fibers are visible under TEM and so TEM 'counts' are invariably higher. Attempts have been made to confine TEM analyses to only those fibers likely to be visible under PCM (PCM-equivalent, or PCMe).[140] Scanning electron microscopy (SEM) with modern instrumentation also offers advantages in asbestos identification and quantitation, and methods (*e.g.* ISO 14966) are being produced.[145] However, even after selection of analytical method and counting rules has been made, there may still be differences in sample preparation methods to consider.[146]

The determination of asbestos in soil has had a shorter history than air monitoring. Methods for the quantitative determination of asbestos in soil have been adapted from methods for determining asbestos in other bulk matrices, including the EPA Method 600-R-93-116, 'Test Method: Method for Determination of Asbestos in Bulk Building Materials'[147] and the NIOSH Method 9002, 'Asbestos (Bulk) by PLM'.[148] Most soil methods include two stages, the first being examination of the bulk soil under a low-power stereomicroscope and removal of all obvious clumps of asbestos which are weighed. Identification of the clumps and identification and quantification in the soil can be performed either by polarized light microscopy (PLM) with dispersion staining or by TEM, with PLM being the cheaper and faster and therefore more common method. For example, a method created specifically for the coarse fraction of Libby, MT soils is the qualitative SRC-Libby-01 (Revision 2).[149] Quantitative methods are however required for risk assessment and accurate risk remediation. The U.S. EPA's national emissions standards for hazardous air pollutants (NESHAPS) defines asbestos containing materials (ACM) as 1% by weight asbestos,[150] and this is a standard that has often been applied to soil until it was determined by the EPA from activity-based sampling that unacceptable airborne fiber levels could be generated from soils containing less than 1% asbestos. Thus methods that claim a limit of quantitation of 1% asbestos may not be applicable to risk assessment or remediation. A method promulgated by the California Air Resources Board (CARB 435) is claimed to be quantitative at 0.25% asbestos.[151] Another quantitative method is that developed for Libby, MT soils, SRC-Libby-03 (Revision 1).[152] The mass percent of asbestos in these methods can be estimated by one of two ways. One is to calculate the mass percent by visually estimating the fraction of the total material in the microscope field of view that is composed by asbestos and equating this fraction to a mass percent. The other is to estimate mass percent by counting the number of asbestos structures present and equating the number count with a mass percent using a standard curve. This second method counts the number of asbestos structures that overlay a fixed point grid. Grids of 100, 400 and 1000 points have been used, with the larger number giving the lowest limit of quantitation. Both TEM[153] and SEM[154] have also been proposed as alternative analytical methods for soil samples. For risk assessment purposes it would be useful to know the proportion of asbestos in soil that might become airborne and so a method for determining the releasable asbestos in soil has been proposed.[155] It must be emphasized that methods for the determination of NOA in soil are not yet standardized to the point of universal acceptance by the analytical community. The absence of validated standard analytical methods can lead to uncertainty in risk assessment. The analytical uncertainty with respect to asbestos may be of similar magnitude to the uncertainties introduced by assumptions in the models to predict exposure and disease.

Conclusion

Asbestos and related hazardous minerals are relatively common around the world. In addition, amphibole minerals not classified as asbestos are even more common. Whether non-asbestiform amphibole particles are a hazard is a matter of on-going debate. Resolution of this issue may have a significant impact on mining and quarrying operations. In the USA, there are major efforts to determine the extent of natural asbestos and fibrous amphiboles. The presence of NOA in certain areas, and the potential for inhalation of airborne fibers resulting from certain activities that disturb these materials is well-documented. The responses of local communities to this hazard span a full spectrum of degrees of concern. In some cases, there are local quarrying operations releasing materials (*e.g.* Silver Bay, Sparta, Libby) that the response can be directed to, but in other cases (*e.g.* Swift Creek, El Dorado, Fairfax Co.), there is not. Responses are the result of interplay between several factors, including the perception of property values, jobs, local politics, health concerns, media attention and the responses of the many levels of government. The complexity of the equation has led to different outcomes in each case; for example local regulations in El Dorado, CA require property sellers to disclose the presence of asbestos, while in Fairfax Co, VA they do not. Each case and each set of solutions has so far been unique, within broad similarities. Those charged with providing advice or regulation might be well-advised to keep in mind the potential need for local adjustments in order to achieve local acceptance. The US EPA and ATSDR have published fact-sheets that describe the problem and several ways to mitigate the hazard, including during construction activities as well as for everyday activities.[156,157] However, this is general guidance and it is up to local authorities to impose specific requirements.

In many of the less developed areas of the world where mineral fiber disease has been recorded, it has frequently been associated with the extraction of asbestos, but whether or not asbestos mining has taken place, disease has either been associated with the use of local stone for building or other purposes, or more often, the use of local soil as 'whitewash' on the outside walls of buildings. In many parts of the world, recommendations to stop the use of local soil as whitewash appear to have reduced the incidence of disease.[158] However, throughout the world, in addition to the potential health affects and the stress of worrying about the future health effects of living in areas where natural mineral fibers occur, there are social effects, including loss of amenity and loss of value of property that may be extremely burdensome, now or in the future. One of the more potentially interesting areas of future research may be to explore the interplay of genetics and exposure in relationship to environmental asbestos risk.[159] The roles of environmental health professionals and their relationships to the other interested parties such as homeowners, developers, local politicians, parents, reporters, and activists, and the conflicts and pressures that result have been explored with respect to a particular instance of NOA in the USA.[160] There are thought-provoking conclusions regarding the issues for scientists involved in science that is still evolving, but where the science is also impacting current legal and regulatory process.

Disclaimer

The findings and conclusions in this report are those of the author(s) and do not necessarily represent the official position of the Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health or any other US government agency. In the interests of examining community response to NOA, several sources have been referenced that are not from the peer-reviewed scientific literature. There is no assurance of the authenticity and accuracy of the statements in these sources.

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