The Geology of Asbestos in the United States and Its Practical Applications

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ABSTRACT

Recently, naturally occurring asbestos (NOA) has drawn the attention of numerous health and regulatory agencies and citizen groups. NOA can be released airborne by (1) the disturbance of asbestos-bearing bedrocks through human activities or natural weathering, and (2) the mining and milling of some mineral deposits in which asbestos occurs as an accessory mineral(s). Because asbestos forms in specific rock types and geologic conditions, this information can be used to focus on areas with the potential to contain asbestos, rather than devoting effort to areas with minimal NOA potential. All asbestos minerals contain magnesium, silica, and water as essential constituents, and some also contain major iron and/or calcium. Predictably, the geologic environments that host asbestos are enriched in these components. Most asbestos deposits form by metasomatic replacement of magnesium-rich rocks. Asbestos-forming environments typically display shear or evidence for a significant influx of silica-rich hydrothermal fluids. Asbestos-forming processes can be driven by regional metamorphism, contact metamorphism, or magmatic hydrothermal systems. Thus, asbestos deposits of all sizes and styles are typically hosted by magnesium-rich rocks (often also iron-rich) that were altered by a metamorphic or magmatic process. Rock types known to host asbestos include serpentinites, altered ultramafic and some mafic rocks, dolomitic marbles and metamorphosed dolostones, metamorphosed iron formations, and alkalic intrusions and carbonatites. Other rock types appear unlikely to contain asbestos. These geologic insights can be used by the mining industry, regulators, land managers, and others to focus attention on the critical locales most likely to contain asbestos.

ASBESTOS

"Asbestos" is not a mineralogical term, but rather a commercial and industrial term used to describe a group of specific silicate minerals that form bundles of long, very thin mineral fibers. When crushed or handled, asbestos bundles readily disaggregate and release microscopic mineral fibers. Asbestos fibers are typically less than a micrometer in diameter and range from several micrometers to hundreds of micrometers in length. The many different ways that asbestos and related terms have been described are summarized in Lowers and Meeker (2002).

The history of asbestos discovery and usage extends back at least 5,000 years (see Ross and Nolan, 2003). Commercial-grade asbestos is composed of long, thin, durable mineral fibers and fiber bundles that exhibit high tensile strength, flexibility, and resistance to heat, chemicals, and electricity (Ross, 1981; Zoltai, 1981; Cossette, 1984; Ross et al., 1984; and Skinner et al., 1988). These properties, especially its exceptional insulation and fire-resistance abilities, have made asbestos widely used in a number of products and industrial applications in the past and present (Virta and Mann, 1994; Ross and Virta, 2001).

Asbestos is most commonly defined as the asbestiform variety of several specific, naturally occurring, hydrated silicate minerals. Asbestos typically includes chrysotile, the asbestiform member of the serpentine group, and several members of the amphibole mineral group, including, but not limited to, the asbestiform varieties of (1) riebeckite (commercially called crocidolite), (2) cummingtonite-grunerite (commercially called amosite), (3) anthophyllite (anthophyllite asbestos), (4) actinolite (actinolite asbestos), and (5) tremolite (tremolite asbestos) (Table 1). Several other amphiboles are known to occur in the fibrous habit (Skinner et al., 1988), and some in the asbestiform habit, such as winchite, richterite (Meeker et al., 2003), and fluoro-edenite (Gianfagna and Oberti, 2001; Gianfagna et al., 2003), which have been linked to respiratory disease clusters. However, these more rigorous academic definitions for amphiboles (Table 2) have generally not been applied in regulatory language.

Historically, chrysotile has accounted for more than 90 percent of the world's asbestos production, and it presently accounts for more than 99 percent of

Table 1. *Ideal end-member compositions of the commonly regulated asbestos minerals. Cation ratios from Leake and others (1997).*

Mineral	End-Member Cation Ratios
Serpentine group	
Chrysotile	$Mg_3Si_2O_5(OH)_4$
Amphibole group	
Asbestiform riebeckite	$\square Na_2(Mg, Fe^{2+})_3Fe^{3+}{}_2 Si_8O_{22}(OH)_2$
(crocidolite)	$Mg/(Mg+Fe^{2+}) < 0.5$
Asbestiform cummingtonite-grunerite (amosite)	$\square Mg_7Si_8O_{22}(OH)_2$ to $\square Fe^{2+}{}_7Si_8O_{22}(OH)_2$
Asbestiform anthophyllite	$\square(Mg, Fe^{2+})_7Si_8O_{22}(OH)_2$ $Mg/(Mg+Fe^{2+}) \geq 0.5$
Asbestiform actinolite	$\square Ca_2(Mg, Fe^{2+})_5 Si_8O_{22}(OH)_2$ $Mg/(Mg+Fe^{2+}) = 0.5 – 0.89$
Asbestiform tremolite	$\square Ca_2(Mg, Fe^{2+})_5 Si_8O_{22}(OH)_2$ $Mg/(Mg+Fe^{2+}) = 1.0 – 0.9$

□ = Empty "A" site in the amphibole structure.

the world production (Ross and Virta, 2001; Virta, 2002). Crocidolite (asbestiform riebeckite) mining in South Africa, Western Australia, and Bolivia, and amosite (asbestiform cummingtonite-grunerite) deposit mining in South Africa account for most of the other asbestos production (Ross and Virta, 2001); all of these asbestos mines are now inactive. Relatively small amounts of anthophyllite asbestos were once mined in Finland (Ross and Virta, 2001). Anthophyllite asbestos was mined in North Carolina until 1979. Very small amounts of actinolite asbestos, anthophyllite asbestos, and tremolite asbestos still may be mined in some countries, such as India, but details on these operations are not available. Asbestos is no longer mined as a primary commodity in the United States, since the last U.S. asbestos mine (a chrysotile mine) closed in California in 2002.

Asbestos as a Health Hazard

Inhalation of airborne asbestos has been linked to a number of serious respiratory diseases and health problems. Diseases such as asbestosis (scarring of the lungs), lung cancer, and malignant mesothelioma have affected many workers in certain asbestos-related occupations (Skinner et al., 1988; Mossman et al., 1990; Guthrie and Mossman, 1993; Nolan et al., 2001; Plumlee and Ziegler, 2003; Roggli et al., 2004; Tweedale and McCulloch, 2004; and Dodson and Hammar, 2006). As a result, during the latter decades of the 20th century, regulatory agencies in the United States and numerous other countries began to define asbestos and set limits for asbestos exposures, such as for those who mine, process, manufacture, and handle asbestos-bearing materials, and also, to a limited extent, in environmental occurrences (Occupational Safety and Health Administration, 1992; Perkins and Harvey, 1993). Asbestos information is available online at http://www.epa.gov/asbestos/ and http://www.atsdr.cdc.gov/asbestos/index.html.

Table 2. *Ideal end-member compositions of other asbestiform amphibole minerals that have been reportedly linked to respiratory disease clusters (Meeker et al., 2003; Gianfagna et al., 2003). Cation ratios from Leake and others (1997) and Gianfagna and Oberti (2001).*

Mineral	End-Member Cation Ratios
Amphibole group	
Asbestiform winchite	$\square(CaNa)Mg_4(Al, Fe^{3+})Si_8O_{22}(OH)_2$
Asbestiform richterite	$Na(CaNa)Mg_5Si_8O_{22}(OH)_2$
Asbestiform fluoro-edenite	$NaCa_2Mg_5(Si_7Al)O_{22}F_2$

□ = Empty "A" site in the amphibole structure.

The fibrous variety of erionite, a member of the zeolite mineral group, is another asbestiform mineral that has been linked to serious respiratory disease and mortality. Fibrous erionite is not regulated as asbestos, but is classified as a known carcinogen to humans. Studies have reported anomalous mortality from mesothelioma in residents of three Turkish villages, which has been linked to chronic exposure to erionite in the local volcanic rocks (Baris, 1991). Fibrous and nonfibrous erionite occur with other zeolite minerals in volcanic tuffs that were altered by low-temperature fluids, particularly saline lake waters (Sheppard, 1996).

Naturally Occurring Asbestos

Asbestos-bearing materials (some pipe wrappings and insulation, as examples) are frequently uncovered in older buildings and structures, causing health concerns for those exposed. As older structures are continually torn down or remodeled, contact with asbestos-bearing materials will likely be of concern for decades to come. The proper handling and disposal of these processed asbestos materials is addressed by a number of federal regulations. Less straightforward is the regulation and management of naturally occurring asbestos (NOA), which has recently gained much attention from regulatory agencies, health agencies, and citizen groups. NOA is asbestos found in-place in its natural state; that is, asbestos minerals in a bedrock exposed by human excavations or by natural weathering.

NOA is of concern because of the potential exposures to microscopic fibers that can become airborne if asbestos-bearing rocks are disturbed by natural erosion or human activities (road construction, urban excavations, agriculture, mining, crushing, and milling). Examples of occupational and environmental exposures to asbestos are described in Nolan and others (2001) and Ross and Nolan (2003).

Recent attention to NOA was spurred by the renewed recognition of high incidences of asbestos-related mortality and respiratory disease in vermiculite miners and residents of Libby, Montana; this disease has been attributed to fibrous amphibole particles within the vermiculite ore body that was mined and milled near the town from 1923 to 1990 (Peipins et al., 2003). Meeker and others (2003) describe in detail the fibrous and asbestiform amphibole minerals intergrown with the Libby vermiculite deposit.

Large areas of exposed ultramafic bedrock in northern California, some now densely populated, have become the focus of recent attention because they may contain chrysotile and tremolite-actinolite asbestos (Churchill and Hill, 2000; Clinkenbeard et al., 2002; Ross and Nolan, 2003; and Swayze et al., 2004).

Local authorities have instituted ways to reduce exposure to naturally occurring asbestos. For example, the Fairfax County Health Department, Virginia, developed an asbestos exposure control plan that is mandated for use in construction projects that excavate asbestos-containing material (ultramafic rock bodies) within the county (Dusek and Yetman, 2002).

Current federal asbestos regulations are available in the Code of Federal Regulations (http://www.gpoaccess.gov/cfr/). However, these asbestos regulations do not specifically address exposures to natural occurrences of asbestos.

APPLICATIONS OF ASBESTOS GEOLOGY

As will be documented in this article, asbestos occurs locally in the following rock types:

- Metasomatized ultramafic rocks, which have been altered by processes of regional or contact metamorphism, such as dunite, peridotite, amphibolite, and pyroxenite, and especially their alteration equivalent, serpentinites.
- Metamorphosed mafic extrusive rocks, especially metabasalt (greenstone), and metamorphosed mafic intrusive rocks, especially metagabbro (diabase, trap rock), which have been subsequently sheared and silicified.
- Dolostones (dolomite, dolomitic marble) and dolomitic limestone that have been metamorphosed and metasomatized by contact or regional metamorphism.
- Iron formation that has been metamorphosed by thermal (contact) metamorphism.
- Alkalic intrusions and carbonatites that are internally metasomatized by magmatic fluids.

Other rock types appear unlikely to contain asbestos. The reported asbestos deposits and occurrences in the United States are hosted by one of the combinations of rock type and geologic setting listed above. It is important to emphasize that even in these rock types, asbestos occurrences are relatively rare and are confined to areas in which ideal asbestos-forming conditions were present (microfracturing, siliceous fluid flow, specific pressure and temperature conditions, and subsequent preservation).

By recognizing that asbestos is formed in certain rock types under specific geologic conditions, the presence or absence of asbestos in an industrial mineral deposit or bedrock terrain can be predicted within reasonable limits. Using the geology of asbestos as a guide, one can focus the costly and time-consuming efforts of asbestos evaluation, monitoring, regulation, and remediation toward those areas most likely to contain asbestos-bearing rock rather than devoting efforts to areas that have minimal NOA potential. Thus, regulatory agencies, health agencies, land managers, mining companies, and ultimately, the general public, benefit if the basic geology of asbestos is considered when asbestos policies are developed.

GEOLOGIC ENVIRONMENTS THAT HOST ASBESTOS

As with any mineral deposit, asbestos forms in particular geologic environments. All asbestos minerals contain magnesium, silica, and water as essential constituents, and some also contain iron and/or calcium as major constituents (Table 1). Thus, the geologic terrains that host asbestos are enriched in these components. Most asbestos deposits form by the metasomatic replacement of magnesium-rich rocks. Asbestos-forming environments typically display shear and/or show evidence that a significant influx of hydrothermal silica-rich fluids occurred at the site. The asbestos-forming processes can be driven by regional metamorphism, contact metamorphism, or magmatic hydrothermal systems. Thus, asbestos deposits, ranging in size from commercial-grade ore bodies to thin impure veinlets or low-grade occurrences, are typically hosted by magnesium-rich rocks (often also iron-rich) that have been metasomatized by a metamorphic or magmatic process.

The discussion that follows is a summary of the rock types and geologic settings that host significant asbestos occurrences within the Continental United States. Similar geologic relationships occur world-wide. The author is aware of no single paper or report before this article that summarizes all of the asbestos-bearing geologic environments in the Continental United States. Detailed geologic and mineralogic descriptions are beyond the scope of this article, but, the papers that are referenced herein provide considerable information on particular U.S. asbestos deposits and districts.

It should be noted that often the same geologic settings that form asbestiform amphiboles will also contain acicular and fibrous amphiboles. In fact, within and adjacent to an amphibole asbestos deposit a variety of amphibole particle forms are usually found, which range from prismatic to acicular to fibrous. See Meeker and others (2003) and Van Gosen, Lowers, and Sutley (2004).

Metamorphosed Ultramafic Rocks

The most well known and largest asbestos deposits in the United States and world-wide are those that have replaced or formed by alteration of an ultramafic rock (Ross and Nolan, 2003). Most commonly, the host ultramafic rock is dunite, peridotite, amphibolite, pyroxenite, or their alteration equivalent, serpentinite. In the Continental United States, asbestos-bearing exposures of ultramafic rocks are most abundant in the westernmost states (Figure 1)—California (Wiebelt and Smith, 1959; Peterson, 1984; Churchill and Hill, 2000; Clinkenbeard et al., 2002; Ross and Nolan, 2003; and Swayze et al., 2004), Oregon (Bright and Ramp, 1965), and Washington (Vhay, 1966)—and in the eastern states (Figure 2) from Alabama to Vermont (Larrabee, 1966, 1971; Van Gosen, 2005).

Large commercial-grade deposits of chrysotile asbestos hosted by altered ultramafic (serpentinite) rocks were mined in California until 2002 (Wiebelt and Smith, 1959; Ross and Nolan, 2003), and chrysotile hosted by metasomatized dunite was mined in north-central Vermont as recently as 1993 (Cady et al., 1963; Chidester et al., 1978; and Van Baalen et al., 1999). In the Eastern United States, large veins and pods of anthophyllite asbestos and tremolite-actinolite asbestos within altered ultramafic bodies were mined in the past at relatively small scales in Georgia, North Carolina, Virginia, Maryland, Connecticut, and Massachusetts (Van Gosen, 2005). The Hippy mine in Yancey County, North Carolina, stockpiled anthophyllite asbestos until 1978. Pennsylvania had some small-scale mining of amphibole asbestos (unspecified type) in the early 1900s, extracted from small altered ultramafic rock bodies.

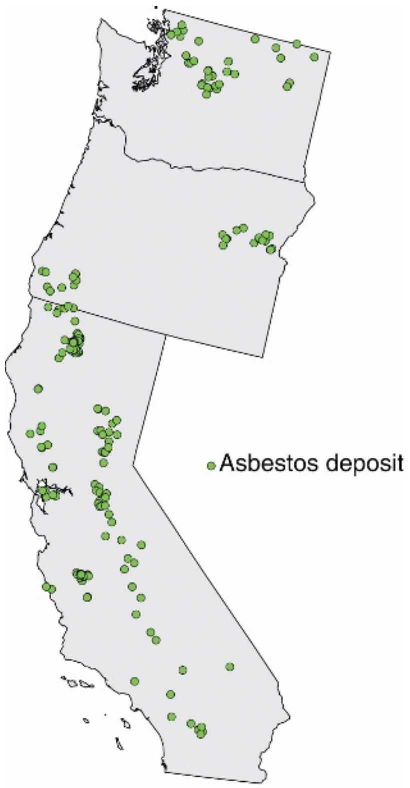

Figure 1. Index map showing the distribution of asbestos deposits that are reportedly hosted by ultramafic rocks in California, Oregon, and Washington. Adapted from U.S. Geological Survey (2006).

Ultramafic rocks, as their name implies, are enriched in mafic (ferromagnesian) minerals, such as olivine, amphiboles, and pyroxenes. This mineralogy makes the ultramafic rocks an ideal host for asbestos formation. In the simplest terms, metasomatism of ultramafic rocks that leads to asbestos formation is caused by an influx of silica-rich fluids into the rock under particular conditions of temperature and pressure. These fluids react with the ferromagnesian minerals in the rock, thereby providing all of the chemical ingredients (Mg, Fe, Ca, Si, and H_2O) necessary to form chrysotile, anthophyllite, and/or species of the tremolite to ferro-actinolite solid solution series (Leake et al., 1997). Metasomatism of ultramafic rocks typically forms serpentinite, a rock composed primarily of the serpentine group minerals antigorite, lizardite, and sometimes chrysotile (Faust and Fahey, 1962). The very presence of serpentinite in an outcrop indicates that the chemical conditions were suitable for asbestos mineral formation.

Fracturing, faulting, shearing, and associated microfracturing accompanied by relatively moderate fluid temperatures and pressures are thought to be other important factors in asbestos formation. Initially, the fracturing likely promotes the serpenti-

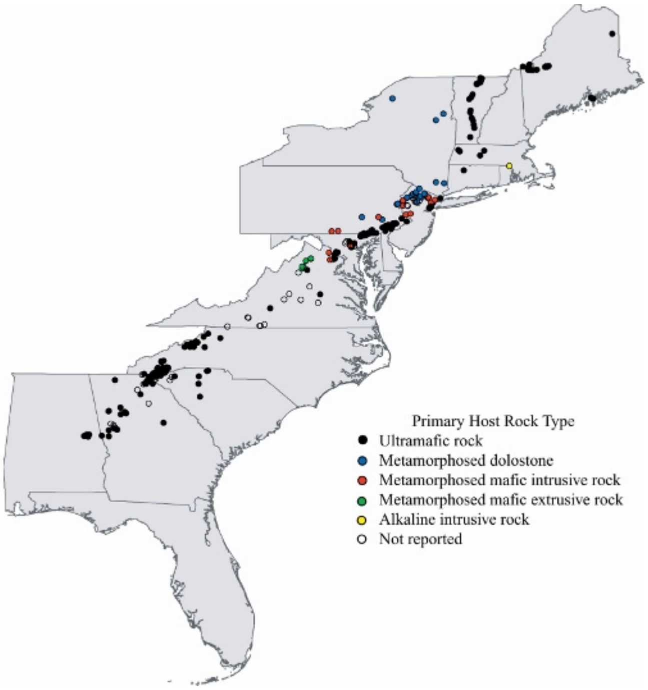

Figure 2. Index map of reported asbestos occurrences in the Eastern United States, showing the primary rock type that hosts each occurrence. Adapted from Van Gosen (2005). A compilation of reported asbestos occurrences in the Central United States is provided in Van Gosen (2006).

nization process by providing conduits and permeability for hydrothermal fluid flow through the ultramafic body (Cady et al., 1963; Chidester et al., 1978). In chrysotile formation (asbestiform serpentine), and probably also in the asbestiform growth of amphiboles, microfractures in the ultramafic host rock likely play an important role. As described by Evans (2004): "Chrysotile is most conspicuously developed in tectonically active environments, where associated lithotypes show marginal greenschist-facies parageneses and antigorite tends to make its first appearance. Chrysotile growth is favored in isotropic stress microenvironments of fluid-filled voids and pores (where it may ultimately crystallize pervasively), and in veins, generally after active hydration in the immediate surroundings has ceased" and "lizardite and chrysotile behave as though they were a stress-antistress mineral pair."

Processes of regional metamorphism were the likely driving mechanism for the heat, pressure, and fluid flow that formed most of the serpentine, chrysotile, anthophyllite asbestos (Figure 3), and tremolite-actinolite asbestos found within metamorphosed ultramafic rock bodies of the Western and Eastern United States. The resultant asbestos deposits in ultramafic rocks vary widely in size, from large commercial-grade bodies (Ross and Nolan, 2003) down to thin veinlets (Rohl et al., 1977; Blake, 1982).

Narrow asbestos-bearing zones (inches to a few feet in width) are also formed by contact metamorphic reactions where felsic igneous masses have intruded into pre-existing ultramafic bodies. An example is described from the Addie district of North Carolina

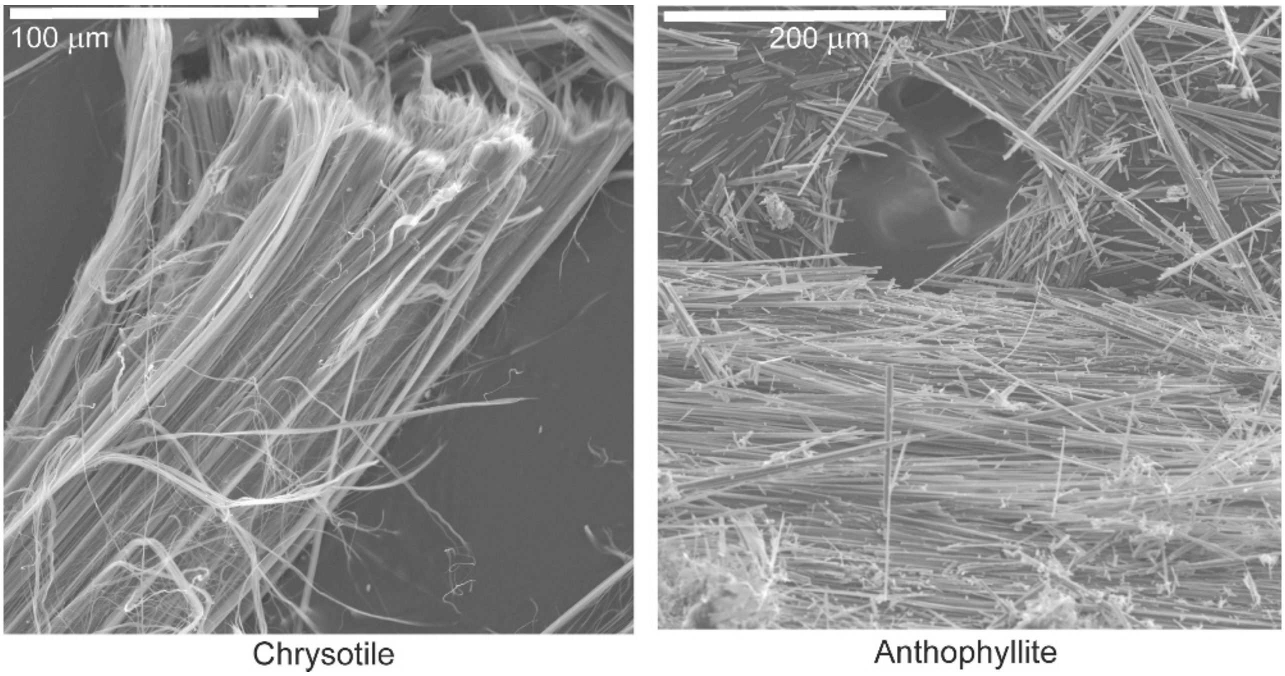

Figure 3. Scanning electron microscope (SEM) photomicrographs showing examples of chrysotile and anthophyllite asbestos, each once mined from veins within regionally metamorphosed ultramafic rock.

(Murdock and Hunter, 1946; Kulp and Brobst, 1954), in which the Day Book dunite deposit contains alteration zones composed of vermiculite (weathered phlogopite), fibrous tremolite and anthophyllite, and talc, along serpentine-rich contacts between dunite masses and intruding pegmatites.

Thus, metamorphosed and/or hydrothermally altered ultramafic rock types—dunite, peridotite, amphibolite, and pyroxenite—and especially their altered counterparts, serpentinites, may merit some level of asbestos evaluation in those areas where they may be disturbed and potentially expose workers or the public to their dust. This type of approach has been instituted by the Fairfax County Health Department, Virginia, for projects that require excavation of ultramafic rock bodies (some with known asbestos deposits) within the county (Dusek and Yetman, 2002).

Metasomatized Mafic Rocks

In the Continental United States, relatively small occurrences of asbestos have been reported within some mafic igneous rocks, including (1) metamorphosed extrusive rocks, especially metabasalt (sometimes called greenstone), which have been sheared and altered, and (2) some metagabbro intrusions (also called trap rock or diabase). A number of examples exist; a few are noted here.

Small amphibole asbestos and serpentine asbestos occurrences, often associated with copper deposits, are reported in metamorphosed mafic volcanic rocks (metabasalt) at several localities within the Catoctin Formation of north-central Virginia (Watson, 1907; Weed, 1911; Thiesmeyer, 1937; and Allen, 1963, 1967). A similar copper prospect in metabasalt (Russel prospect), located in Pennsylvania, is reported to contain crocidolite (Geyer et al., 1976). Features of shear and siliceous alteration are described at these sites.

Minor occurrences of amphibole asbestos have been described at some trap rock (metagabbro or diabase) quarries in the Eastern United States. As examples, in New Jersey, crocidolite is reported in Cope's quarry (Germine, 1981; Germine and Puffer, 1981) and asbestiform actinolite in the Prospect Park quarry (Mason, 1960; Peters and Peters, 1978; Germine, 1981; and Germine and Puffer, 1981). In southeastern Pennsylvania, Geyer and others (1976) report crocidolite in the Deyer quarry and asbestiform tremolite in the Teeter quarry. In northern Virginia, asbestiform tremolite-actinolite is reported in the Centreville (Fairfax) quarry (Medici, 1972; Bernstein, 1980) and asbestoform amphibole in the Arlington quarry (Dietrich, 1953). These amphibole asbestos occurrences are apparently minor in size and extent, limited to thin veins in sheared areas of the metagabbro exposed in the pits. Thus, these asbestos-bearing zones can be identified and avoided with careful planning of the mining operations.

Metamorphosed Dolostones

Chrysotile and asbestiform calcic and sodic-calcic amphiboles can form in dolostone and dolomitic limestone under some conditions of contact or regional metamorphism. The asbestos deposits that replace dolomitic rocks occur in a wide variety of styles, ranging from multiple commercial-grade veins of chrystotile to minor amounts of asbestiform amphibole found as an accessory mineral within a larger mineral deposit, such as a body of talc. Dolostone-hosted asbestos also occurs in a variety of geologic settings, as is demonstrated below.

A chrysotile mining district with significant past production lies in Gila County, Arizona, north and northeast of Globe. From 1913 to 1966, about 75,000 tons (68,000 tonnes) of chrysotile asbestos was produced from more than 160 mines; production from an additional 60-70 occurrences in the region is unknown (Harris, 2004). Asbestos mining in this region ended in the early 1980s. The chrysotile deposits of the Globe region formed through contact metamorphism. Chrysotile veins formed in serpentinized contact zones where diabase intruded the Mescal Limestone (dolomitic limestone). The chrysotile occurs primarily as cross-fiber veins, with occasional slip-fiber examples. The asbestos is hosted by layers of serpentine, up to 2-ft (0.6-m) thick, which replace the dolomitic limestone adjacent to the diabase. Single to multiple veins of chrysotile occur in each serpentine layer. The chrysotile veins vary from microscopic in size to a maximum of 14-in. (36-cm) thick, with most less than 2-in. (5-cm) thick (Wilson, 1928). Detailed descriptions of the chrysotile deposits of the Globe region are provided by Wilson (1928), Stewart (1955), Moore (1968), and Bromfield and Shride (1956).

Other examples of asbestos formed by contact metamorphism are found in the southern Death Valley region of California. These deposits are also the best examples in the United States of talc ores formed by contact metamorphism. The southern Death Valley deposits are talc-tremolite rocks that are geologically similar across the region, consistently associated with a carbonate horizon of the Crystal Spring Formation of Proterozoic age (Wright, 1968). In this interval, thick regionally persistent gabbroic sills intruded dolomite during the Mesoproterozoic, and formed laminated talc-tremolite-rich rock along

Figure 4. Site of the historic Pleasanton talc mine in Death Valley National Park, California, an example of the talc deposits of the southern Death Valley region (Wright, 1968; Van Gosen, Lowers, and Sutley, 2004; and Van Gosen et al., 2004b). The talc-tremolite rock formed through metasomatic reactions caused by the intrusion of the gabbro sill into the siliceous dolomite.

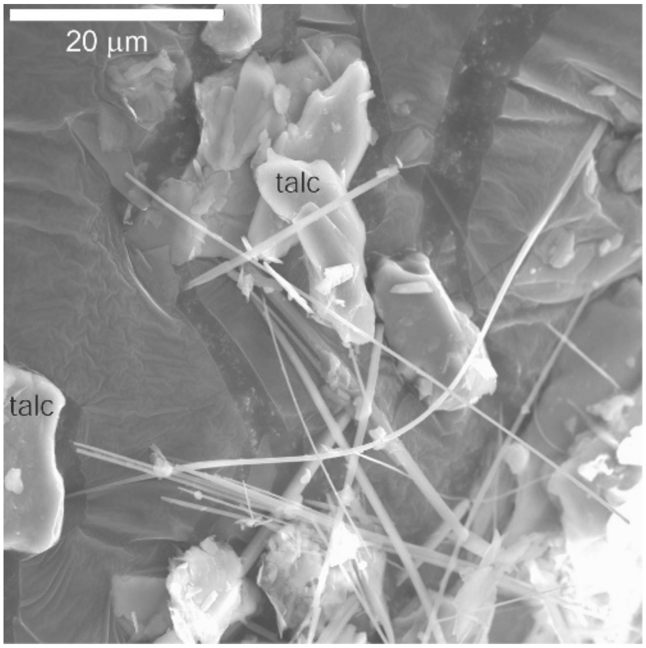

Figure 5. SEM photomicrograph of asbestiform sodic-calcic amphibole particles intermixed with platy talc in talc-tremolite ore from a southern Death Valley deposit of the type shown in Figure 4 (Van Gosen, Lowers, and Sutley, 2004; Van Gosen et al., 2004b).

the sill-dolomite contacts (Figure 4). Metasomatic reactions during sill emplacement caused the massive replacement of dolomite by talc-tremolite-rich bodies, which are approximately 500–5,000-ft (150–1,500-m) long and 10–100-ft (3–30-m) thick. Relative proportions of talc versus tremolite vary across the deposits, and either mineral can predominate within any particular deposit. Petrographic examinations of the ore show that most of the talc is platy, intergrown with tremolite that is primarily prismatic in shape; observations suggest that the intergrown talc and tremolite were contemporaneous. Examination of the talc-tremolite rock by scanning electron microscopy, accompanied by energy-dispersive spectrometry analyses, found scattered occurrences of asbestiform tremolite, asbestiform winchite, and asbestiform richterite, including bundles of fibers and loose fibers (Figure 5) (Van Gosen, Lowers, and Sutley, 2004; Van Gosen et al., 2004a, 2004b). In contrast, other talc deposits of the Death Valley region, which also replaced dolostones but were created by hydrothermal fluids heated by deeply buried magmas, do not contain amphiboles (Van Gosen et al., 2004b).

Fibrous varieties of talc, tremolite, and anthophyllite, formed by the regional metamorphism of dolomitic carbonates (now dolomitic marble), occur in the large tremolite-talc deposits of the Gouverneur talc mining district of upstate New York (Engel, 1962; Hull et al., 2002; Van Gosen, Meeker, and Brownfield, 2004; and Webber et al., 2004). For more than 30 years, a debate has ensued as to whether the fibrous amphiboles in the Gouverneur talc ores meet the criteria of asbestos. The debate has centered on the complex and unusual transitional fibers that are a trademark of the Gouvernuer talc ores, and more specifically, whether these particles represent asbestos. These transitional fibers are fibrous mineral particles composed partly of talc and partly of anthophyllite.

Small occurrences of asbestiform amphiboles in Precambrian dolomitic marbles have been noted at several locations in New Jersey (Germine, 1981; Germine and Puffer, 1981; and Van Gosen, 2005). As examples, Germine (1986) describes asbestiform and non-asbestiform (prismatic and acicular) tremolite-actinolite collected from two marble quarries in Franklin and Sparta, Sussex County, New Jersey.

Skarn deposits, specifically mineral deposits formed by the intrusion of felsic magmas into dolomitic carbonate rock, appear to be another favorable environment for the formation of amphibole asbestos or chrysotile. Tremolite or actinolite is often noted in the replacement bodies of skarn systems, in association with a variety of calc-silicate minerals. Thus, it would not seem surprising to discover amphibole asbestos within a metal-rich skarn deposit, garnet skarn, wollastonite skarn, or marble deposit that formed from an igneous intrusion into a dolomitic host rock. As an example, crocidolite and fibrous actinolite are minor accessory minerals in the iron-rich skarn at the former Iron Mountain iron mine, near Iron Mountain, southeastern Missouri

(Allen and Fahey, 1956; Murphy and Ohle, 1968; and Kisvarsanyi and Kisvarsanyi, 1989). Asbestos is reported to occur in the large copper ore bodies of the Bingham district, Utah, which have replaced highly metamorphosed, silicified limestone (dolomitic) that borders the intrusive felsic stock. The basic gangue mineralogy of the Bingham copper replacement ores (skarn deposits) includes garnet, wollastonite, diopside, tremolite, asbestos, and specularite (Hunt, 1924). Another example is the skarn deposit that was once mined at the Tilly Foster iron mine in southeastern New York State (Van Gosen, 2005). This iron skarn is reported to contain small amounts of vug-filling actinolite asbestos, chrysotile, and crocidolite (Januzzi, 1959, 1961). In the New Jersey-New York area, other skarn deposits that contain minor amounts of asbestos are listed in Van Gosen (2005).

Metamorphosed Iron Formations

Commercial deposits of crocidolite (asbestiform riebeckite) in metamorphosed banded iron formation (ironstone) were mined extensively in South Africa, Western Australia, and Bolivia (Virta and Mann, 1994; Miyano and Beukes, 1997; Ross and Virta, 2001; and Virta, 2002). Amosite (asbestiform cummingtonite-grunerite) was mined from contact-metamorphosed layers of banded iron formation in South Africa. (The commercial term "amosite" is derived from "Asbestos Mines of South Africa".) None of these asbestos mining districts is active today. Unfortunately, these crocodilite and amosite mines have left behind a harsh legacy of severe respiratory disease and mortality for a high proportion of their former employees (Gibbons, 2000; Dodson and Hammar, 2006).

Banded iron formation is well represented in the Precambrian craton of Minnesota, Wisconsin, and Michigan. None of the iron formation in this region, nor any other iron formation in the United States, reportedly contains a commercial-grade deposit of crocidolite or amosite. However, the banded iron formation of the Mesabi Range of Minnesota (White, 1954), does have an asbestos controversy; it also provides an example of applying geologic information to asbestos issues.

The Precambrian-age Biwabik (Iron) Formation extends for roughly 120 miles (190 km) in the Mesabi Range from Grand Rapids to near Babbitt, Minnesota. The Biwabik Formation has been an enormous source of taconite, a commercial (and loosely applied geologic) term for the low-grade iron ore that has been mined in this region (banded iron-formation composed of ferruginous chert and slate). The taconite ore from the Mesabi Range is mined, processed, and formed into taconite pellets, which have been used as an iron source by the U.S. steel industry since 1955 (Great Lakes Research Advisory Board, 1975).

In 1955, the Reserve Mining Company began commercial operation of the Silver Bay taconite processing plant on the shore of Lake Superior near Silver Bay, Minnesota. This plant produced millions of tons of iron ore pellets per year, with a high production of 10.8 million tons (9.8 million tonnes) of pellets in 1966 (Great Lakes Research Advisory Board, 1975). The waste rock (tailings) at the plant site was disposed of as a slurry mixture that was piped into Lake Superior.

In the early 1970s, tests of the Duluth, Minnesota, water supply, drawn from Lake Superior, indicated that the water contained asbestiform particles of cummingtonite-grunerite. These particles were attributed to the taconite tailings that were being piped into Lake Superior by Reserve Mining Company. Water studies by state and federal agencies were accompanied by extensive litigation against Reserve Mining Company in the early 1970s, which climaxed with a U.S. District Court order that shut down the Silver Bay taconite processing facility in April 1974. The history of the Reserve Mining Case and water sample analyses are detailed in Great Lakes Research Advisory Board (1975) and discussed in Carter (1974). The Reserve Mining Case brought attention to the potential asbestos content of the taconite ores of the eastern Mesabi Range of Minnesota, which was the taconite material processed at Silver Bay.

Geologic and mineralogical studies of the banded iron formation of the Biwabik Formation in the Mesabi Range were conducted by Gunderson and Schwartz (1962), French (1968), and Morey and others (1972). These studies revealed that amphiboles within the taconite (mostly grunerite and lesser cummingtonite) were limited to the eastern Mesabi Range, coincident with the area where the Biwabik (Iron) Formation was thermally altered by the intrusion of the Duluth Gabbro Complex (thermal contact metamorphism with little fluid influence). French (1968) found that within several miles of the Duluth Gabbro Complex the moderately to highly (contact) metamorphosed taconite contains abundant grunerite in some layers. French (1968) described some of this grunerite as fibrous in habit. In contrast, he found that the unaltered (unmetamorphosed) taconite is devoid of amphibole of any type; the unmetamorphosed taconite extends from the western limit of the Mesabi Range northeastward to approximately the town of Aurora.

The asbestos issues surrounding taconite ores of the Mesabi Range remain controversial. Does the fibrous grunerite in the taconite ore bodies meet the morphological criteria of asbestos? Have taconite workers been harmed? While these issues remain, the earlier geologic studies can be used to help narrow the geographic extent of the debate. French (1968) showed that amphiboles, including fibrous grunerite, formed exclusively in the contact-metamorphosed taconite of the eastern Mesabi Range district. Therefore, asbestos studies and debate in the future can focus only on the taconite deposits of this area. This example demonstrates how geologic information can be used to define the geographic areas where asbestos may exist versus those areas where it is unlikely to exist.

Alkalic Intrusions and Carbonatites

Alkaline rocks and carbonatites are a particularly diverse group of igneous rocks that are widely distributed in the United States (Woolley, 1987). None of the alkaline intrusions in the United States are known to contain commercial asbestos deposits (mined specifically for asbestos). However, several carbonatites in the United States and some alkalic intrusions do contain asbestiform amphiboles (sodic-calcic and calcic amphiboles) as accessory minerals.

A notable example of an asbestos-bearing alkaline intrusion is the Rainy Creek Complex near Libby, Montana, the host for a world-class vermiculite deposit that was mined from 1923 to 1990. The Libby (Rainy Creek or Zonolite) vermiculite deposit formed through supergene alteration of the Rainy Creek Complex, which is a large zoned pyroxenite pluton with a central biotite-rich pyroxenite core. A younger mass of syenite cuts the outer zones of the pluton, and alkalic syenite dikes cut the biotitite core. A nearby small mass of nepheline syenite and fenitization of the meta-sedimentary rocks surrounding the pluton suggest that a carbonatitic mass occurs at depth (Boettcher, 1967).

Former vermiculite miners and the residents of Libby, Montana, have unusually high rates of asbestos-related respiratory disease and mortality, which has been attributed to amphibole mineral fibers intergrown with the Libby vermiculite deposit (Peipins et al., 2003). Fibrous to asbestiform amphiboles occur in hydrothermal veins and veinlets and as the alteration products of pyroxenes in the intrusive complex and vermiculite ore body (Boettcher, 1967; Meeker et al., 2003). A detailed sampling and analysis of amphibole-rich rock from the Libby (Rainy Creek) vermiculite deposit was performed by Meeker and others (2003). They found that: "The range of amphibole compositions, determined from electron probe microanalysis and X-ray diffraction analysis, indicates the presence of winchite, richterite, tremolite, and magnesioriebeckite." They show that nearly complete solid solution occurs in the Libby amphiboles between the ideal end-member compositions, as defined by Leake and others (1997). Also, the Libby amphibole particles display a continuum of morphologies, ranging from prismatic crystals to asbestiform fibers; most of the Libby amphiboles have a shape between prismatic and asbestiform. Meeker and others (2003) observed that Libby winchite, richterite, tremolite, and possibly magnesioriebeckite occur in fibrous or asbestiform habit.

A least one carbonatite in Colorado—the Gem Park Complex, which straddles part of the Custer and Fremont County boundary—also contains deposits of vermiculite and fibrous to asbestiform amphibole (Van Gosen et al., 2005). The Gem Park Complex consists mostly of pyroxenite and gabbro, cut by abundant carbonatite dikes and irregular bodies (Parker and Sharp, 1970). This complex is further cut by minor dikes and bodies of lamprophyre, syenite porphyry, and nepheline syenite pegmatite. A fenite mass lies near the center of the complex. The entire intrusive complex is interpreted to be underlain by a large carbonatite body (Parker and Sharp, 1970; Armbrustmacher, 1984). The Gem Park Complex contains abundant amphibole fibers and some concentrations of asbestiform fibers, semiquantitatively determined (by energy-dispersive spectroscopy) to be winchite, richterite, and riebeckite (Van Gosen et al., 2005).

The Mountain Pass district lies in San Bernardino County, California, near the Nevada border in the southern Death Valley region (Woolley, 1987). In the district, the Sulphide Queen carbonatite contains a world-class-size reserve of rare-earth-bearing oxide minerals. This deposit was mined for use in rare earth commodities from 1954 until recently (Castor and Nason, 2004). A variety of minerals are reported in carbonatite in association with the rare-earth minerals, including crocidolite (asbestiform riebeckite) (Olson et al., 1954).

Crocidolite reportedly occurs within a mass of alkaline granite exposed on Beacon Pole Hill, near Cumberland, Rhode Island (Chester and Cairns, 1887).

An alkaline syenite dike that contains fluffy clumps of asbestiform amphibole crops out in the former Camp Albion mining district, Boulder County, Colorado (Figure 6). The syenite dike contains an unusual assemblage of copper-bearing pyrite, galena, sphalerite, calcite, feldspar, quartz, and pyroxene, as well as tufts of an amphibole with well developed

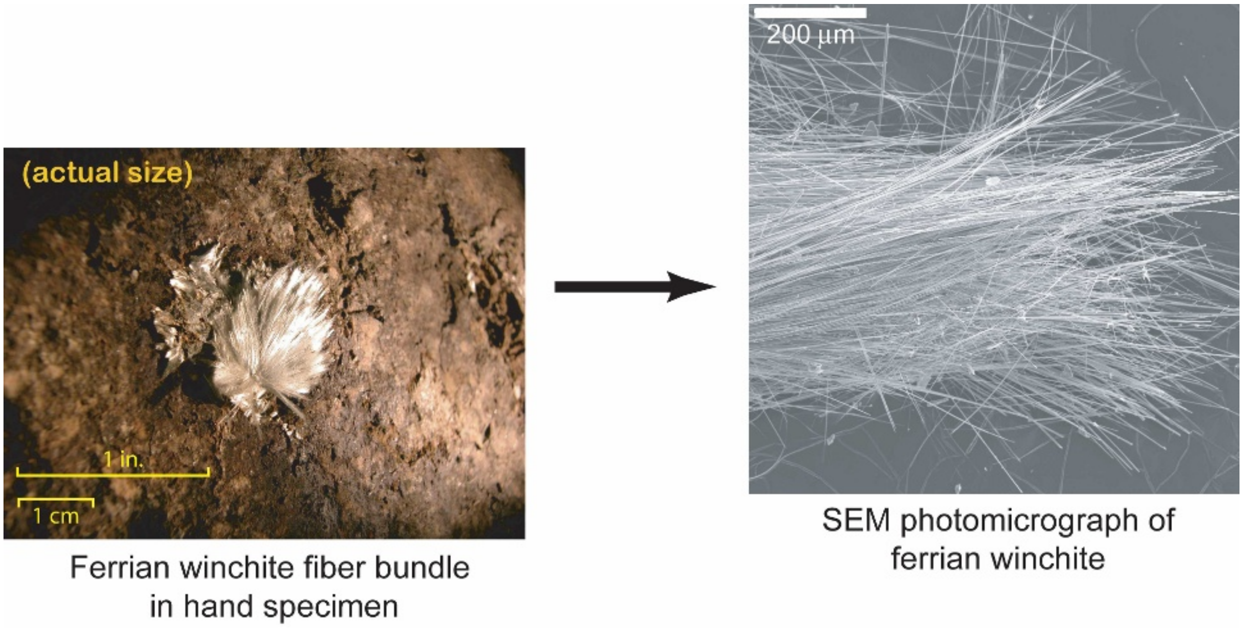

Figure 6. Example of the asbestiform ferrian winchite that occurs in a syenite dike in the historic Camp Albion mining district, Boulder County, Colorado (Wahlstrom, 1934).

asbestiform habit (Wahlstrom, 1934). Results of x-ray diffraction, wavelength dispersive x-ray fluorescence spectrometry, and scanning electron microscopy accompanied by energy dispersive x-ray spectrometry (unpublished study by the author) suggest that this asbestiform amphibole is ferrian winchite.

The metasomatism and asbestos formation in each of the alkaline igneous rocks described above is thought to be caused by magmatic hydrothermal fluids, with no obvious relationship to regional or contact metamorphism.

As noted by these examples, fibrous to asbestiform amphibole are known to occur in some alkaline rocks in the United States, especially in carbonatites. Perhaps the association between alkaline igneous rocks and asbestos has been under-reported or under-recognized in the United States.

CONCLUSIONS

NOA is term that has become widely used to describe asbestos mineral deposits found in-place; that is, asbestos occurring in the rocks in which it formed or in soils formed from those rocks. NOA is in contrast to asbestos that has been processed and used in a product or application. Inhalation of asbestos fibers caused by exposures in some asbestos-related occupational settings has been recognized for several decades as the cause of some serious respiratory diseases, such as asbestosis, mesothelioma, and some lung cancers. Less understood, but gaining more recent attention, are potential airborne asbestos exposures that may result from disturbance of NOA deposits. Natural weathering of NOA-bearing bedrock as well as human activities (road building, construction, agriculture, mining, and recreational pursuits, as examples) can disaggregate the mineral fibers from rock and soils and release them airborne, thereby potentially harming those that breathe in the dusts created. Thus, science-based control measures can be established in areas where NOA-bearing bedrock and soils are shown to exist. For example, in the United States and worldwide, specific magnesium-rich rock types host the known asbestos deposits. These rock types include metamorphosed and altered ultramafic rocks (especially serpentinites), sheared and altered metabasalts and metagabbros, dolomitic marbles, metamorphosed dolostones, contact metamorphosed iron formations, alkaline intrusions, and carbonatites. On local and regional scales, this geologic information, combined with recognition of known asbestos occurrences, can be applied to practices that attempt to mitigate asbestos exposures.

HAZARD MITIGATION

NOA has become an important issue in the United States for many federal, state, and county health and regulatory agencies. Recently, more citizen groups have expressed concerns and a growing interest in potential asbestos exposures from disturbed natural environments. Public agencies and private industry find their resources are stretched thin as they attempt to evaluate, monitor, and plan for the wide variety of natural asbestos-bearing environments that exist. Thus, it is especially important to recognize and understand the basic geology of asbestos and then apply this knowledge to the study and management of exposure scenarios. A geologic approach that allows one to focus on the bedrock terrains most likely to contain asbestos (summarized in this article), while eliminating the terrains that are unlikely to host asbestos, benefits all involved through time and cost savings, and thereby potentially saving lives.

Airborne dusts are most likely to be generated in arid to semi-arid environments where moisture and vegetation are often lacking. Even in temperate regimes, however, erosion, wind, road construction, building excavation, agriculture, and mining and crushing of asbestos-bearing rocks can expose workers, residents, and perhaps recreational users to airborne asbestos. Reducing exposures to asbestos-bearing dust, regardless of the asbestos type, is the ultimate goal of the regulatory and health management agencies and public groups that are concerned with natural asbestos issues.

The Fairfax County Health Department, Virginia, has enacted procedures that attempt to minimize asbestos exposures in their county (http://www.fairfaxcounty.gov/hd/downloads.htm). They recognized that the county's asbestos deposits are hosted in ultramafic rocks of the Piney Branch Complex. They used published geologic maps to delineate the Piney Branch complex within Fairfax County and then developed asbestos control plans that must be used in construction projects that excavate the mapped ultramafic rocks. The county's asbestos control procedures, described in Dusek and Yetman (2002), require construction contractors to: (1) monitor dust emissions at the construction site and its vicinity during the project, (2) comply with specific ambient air asbestos standards, and (3) use dust control measures, such as using ample water to suppress dusts that are created.

In the western Sierra foothills region of California, asbestos occurs locally in regionally metamorphosed, serpentinized ultramafic rocks (Churchill and Hill, 2000; Clinkenbeard et al., 2002; Ross and Nolan, 2003; and Swayze et al., 2004). The California Geological Survey is creating maps of northern California showing those areas most likely to host asbestos (http://www.consrv.ca.gov/CGS/minerals/hazardous_minerals/asbestos/index.htm). The California Air Resources Board monitors airborne asbestos concentrations using strategically placed ambient air monitors (http://www.arb.ca.gov/toxics/asbestos/airmon.htm). The U.S. Environmental Protection Agency is also conducting studies of the NOA in this region (http://www.epa.gov/region09/toxic/noa/).

These relatively recent efforts that aim at controlling exposures to NOA include: (1) identifying the natural bedrock sources of NOA, (2) monitoring and interpreting dust emissions, and (3) developing ways to minimize public and worker exposure to dusts generated from NOA-bearing bedrock. Similar efforts to manage asbestos throughout the United States should recognize that asbestos deposits are not limited to serpentinized ultramafic rocks occurring only in California and Virginia. Asbestos can also occur locally in similar rocks elsewhere, as well as in sheared and altered metabasalts and metagabbros, dolomitic marbles, metamorphosed dolostones, contact metamorphosed iron formations, and alkaline intrusions and carbonatites. The evaluation and management of natural asbestos at a variety of scales should include an inventory of known asbestos occurrences in an area supplemented by a basic understanding of asbestos geology.

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