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# Using the geologic setting of talc deposits as an indicator of amphibole asbestos content

Bradley S. Van Gosen · Heather A. Lowers · Stephen J. Sutley · Carol A. Gent

**Abstract** This study examined commercial talc deposits in the U.S. and their amphibole-asbestos content. The study found that the talc-forming environment directly influenced the amphibole and amphibole-asbestos content of the talc deposit. Large talc districts in the U.S. have mined hydrothermal talcs that replaced dolostone. Hydrothermal talcs, created by siliceous fluids heated by magmas at depth, consistently lack amphiboles as accessory minerals. In contrast, mineable talc deposits that formed by contact or regional metamorphism consistently contain amphiboles, locally as asbestiform varieties. Examples of contact metamorphic deposits occur in Death Valley, California; these talc-tremolite deposits contain accessory amphibole-asbestos. Talc bodies formed by regional metamorphism always contain amphiboles, which display a variety of compositions and habits, including asbestiform. Some industrial mineral deposits are under scrutiny as potential sources of accessory asbestos minerals. Recognizing consistent relations between the talc-forming environment and amphibole-asbestos content may be used in prioritizing remediation or monitoring of abandoned and active talc mines.

**Keywords** Talc · Amphibole-asbestos · Geologic setting · Hydrothermal · Metamorphic · USA

## Introduction

The presence of amphibole asbestos as minor accessory minerals in some talc deposits, and its potential health

impacts on the human respiratory system, have been the focus of considerable research and contentious debate for at least 30 years (Goodwin 1974; Occupational and Safety and Health Administration 1992). Talc-asbestos issues have drawn renewed attention, such as news reports in 2000 contending that the fibrous talc used to add strength to the best-selling brands of children's crayons contained amphibole asbestos (Beard and others 2001). To investigate the extent and character of amphibole minerals in talc deposits, a group at the U.S. Geological Survey (USGS) is examining the relationships between amphiboles and talc in U.S. deposits. This study, involving field examinations and sampling, laboratory analyses, and an extensive literature review, has revealed that a consistent relationship occurs within large (commercial) and small U.S. talc deposits—that is, the primary talc-forming environment directly controlled the ultimate amphibole content of the talc deposit.

Talc deposits are the products of metasomatism caused by regional metamorphism, contact metamorphism, or hydrothermal processes (meteoric fluids or brines heated by distant or buried intrusions). Two of these talc-forming mechanisms—contact metamorphism and hydrothermal processes—are well represented by large, historically mined deposits in the Death Valley region of southern California. Results of field and laboratory studies on these Death Valley deposits, described herein, reflect the consistent associations of amphibole-rich talc deposits with contact metamorphism versus amphibole-poor talc with hydrothermal processes.

A number of U.S. talc deposits of commercial size (under past or present economic conditions) were formed by metasomatic processes driven by regional metamorphism; these large bodies consistently contain talc intergrown with amphiboles, such as tremolite and (or) anthophyllite. Debate over the asbestos mineral content (major versus trace amounts) within these talc-amphibole deposits is the result of differing interpretations of the predominant habit (asbestiform versus non-asbestiform) of the amphibole particles. The complicating factors that face analysts examining this type of talc ore material are discussed.

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## Asbestos

Asbestos is a commercial-industrial term with a long history, and is not a mineralogical definition. "Asbestos" in the

latter half of the 20th century became widely used in regulatory language to refer to well developed, long, thin particles (fibers or fibrils) and fiber bundles of specific mineral compositions, which have fulfilled particular industrial applications. In the U.S., asbestos is most commonly defined as the asbestiform variety of 6 naturally occurring hydrated silicate minerals; these include chrysotile, the asbestiform member of the serpentine group, and five minerals of the amphibole group: 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) (Occupational Safety and Health Administration 1992). The qualities of asbestos that make it useful and desirable for commercial use are its high tensile strength, flexibility, and its resistance to heat, chemicals, and electricity.

The inherent properties of asbestos—fibers that are durable, long, and thin—appear to contribute to the toxicity of these mineral particles when lodged inside the human respiratory system (Stanton and others 1981; Wylie and others 1993). Occupational exposures to asbestos have been linked to asbestosis (scarring of the lungs, “pulmonary interstitial fibrosis”), lung cancer, and malignant mesothelioma (tumor development within the pleural membrane lining the chest cavity and (or) in the peritoneum lining the abdominal and pelvic walls and their viscera) (Skinner and others 1988; Mossman and others 1990; Guthrie and Mossman 1993; Nolan and others 2001). Historically, chrysotile has accounted for more than 90% of the world’s asbestos production, and presently over 99% of the world production (Ross and Virta 2001; Virta 2001, 2002). Whereas mining, processing, and use of chrysotile has been much more common, several studies suggest that amphibole asbestos, even when occurring as a minor accessory in chrysotile deposits, may be the primary cause of mesothelioma in asbestos-related occupations (Ross 1981, 1984, 2001; Mossman and others 1990; Browne and Wagner 2001; Gibbs 2001; Langer 2001; Pooley 2001a, 2001b). As noted by Mossman and others (1990, p. 296): “The persistence of amphiboles in human lungs may be attributed to their increased ability to penetrate the peripheral lung, lack of clearance, or durability”. Wagner and others (1960) described the high rates of malignant mesothelioma in workers and nearby residents of crocidolite (asbestiform riebeckite) mines in the Cape Province of South Africa. Following publication of that study in 1960, mesothelioma became increasingly recognized as an occupational risk in the mining, milling, and handling of rocks that contain amphibole asbestos and their by-products.

In recent years, there has been a renewed focus upon the hazards related to inhalation of amphibole asbestos; in particular, exposures due to the mining and processing of some amphibole-bearing industrial mineral deposits, as well as environmental exposures to amphibole-rich bedrock, such as road cuts and excavations that expose asbestos-bearing rock (Browne and Wagner 2001). For example, unusually high incidences of asbestos-related mortality and respiratory disease in the small town of Libby, Montana, have been attributed to amphibole

mineral fibers intergrown with the vermiculite deposits mined and milled near the town from 1923 to 1990 (U.S. Senate Committee on Environment and Public Works 2000; Dearwent and others 2000). The California Division of Mines and Geology has mapped outcrops of ultramafic rocks in California to indicate country rocks with the potential to host chrysotile and actinolite-series asbestos (Churchill and Hill 2000). Other examples of occupational and environmental exposures to asbestos are described in Nolan and others (2001).

The history and study of naturally occurring asbestos, its associated health impacts, and the multiple, complex issues that revolve around asbestos are discussed in Campbell and others (1977), Ross (1981), Zoltai (1981), Levadie (1984), Skinner and others (1988), Mossman and others (1990), Occupational Safety and Health Administration (1992), Guthrie and Mossman (1993), Nolan and others (2001), and Virta (2001, 2002). Current federal regulations are provided in the Code of Federal Regulations (CFR), including regulations on occupational exposures to asbestos excepting construction and ship-related work (CFR 29, part 1910.1001); CFR regulations are updated as needed on July 1.

## Exploitable talc deposits and amphiboles

Talc is a hydrous silicate with an idealized composition of  $Mg_3Si_4O_{10}(OH)_2$ , but can contain major amounts of Fe, minor Al and F, and trace Mn, Ti, Cr, Ni, Ca, Na, and K (Evans and Guggenheim 1988; Greenwood 1998). Significant talc deposits occur in the U.S. in the Appalachians, from Vermont to Alabama, in the West in Montana, California, Nevada, Washington, Idaho, and New Mexico (Piniakiewicz and others 1994). Large deposits also occur in Texas, and small soapstone mines once operated in Arkansas, but economic deposits are otherwise lacking between the Appalachians and the Rocky Mountains. Commercial talc deposits have replaced two general rock types: (1) Dolostone (dolomite or dolomitic marble), which were selectively replaced by reactions with large volumes of heated waters carrying silica in solution, mobilized by magmatic or metamorphic mechanisms. The dolostone-hosted replacement deposits range from cm-thick pods to the 29-m-thick talc body at the Treasure Chest mine near Dillon, Montana (Berg 1979). Today and in the past, the largest talc producing districts in the U.S. exploited talc deposits replacing dolostone, and to a lesser extent, magnesite. (2) The second common talc hosts are ultramafic rocks, mainly dunites and peridotites, altered by metasomatism through contact or regional metamorphism. Magnesium silicates in these rocks reacted with  $SiO_2$ -saturated aqueous pore fluids during metamorphism to form nearly monomineralic bodies of talc adjacent to zoned sequences of talc-carbonate-, calcic amphibole-chlorite-, and chlorite-dominant zones in addition to complexly mixed zones (described by Sanford 1982). These deposits

form rinds on the ultramafic bodies or nearly replace them; they are typically tabular or lenticular talc bodies that can reach 100 m in thickness and extend more than 300 m in length. Large deposits of this type are mined in Vermont, and smaller deposits have been mined in other eastern states, California, and Texas. The ultramafic-hosted deposits have been equally important sources of pure talc and darker talc (soapstone), the dark talcose bodies owing their coloration to amphibole, serpentine, and chlorite impurities (Piniakiewicz and others 1994). The host rock composition and process of formation determines the qualities of talc, which in turn affects the industrial applications of a particular deposit. The grain size and shape, color, and purity of talc influence its uses (Piniakiewicz and others 1994). In addition, the talc-forming mechanism—hydrothermal processes, contact metamorphism, or regional metamorphism—directly influenced the ultimate amphibole content of the talc ore body, described below through examples. Within a single mineral deposit, such as some talc ore bodies, amphibole crystals may range in habit from blocky to prismatic to acicular to asbestiform. In describing amphibole asbestos, Wylie (2000, p. 56) notes that: “Amphibole-asbestos fibrils range in width from about 1 to 0.01  $\mu\text{m}$ ” and “individual fibrils and bundles of fibrils may attain lengths of hundreds to thousands of times their widths”.

## Study methods

Samples of talc ore material were collected at several mine sites, which are described below. Each sample was collected as a composite, containing at least 30 pieces of

randomly selected talcose rock at each particular sample spot. The samples are intended to represent the talcose material mined at each site, collected mainly from mines that are inactive and abandoned, excepting those samples collected from an active open pit of the Yellowstone mine, southwest Montana.

Dust coating the inside of the plastic sampling bag was examined using a JEOL 5800-LV scanning electron microscope (SEM), equipped with an Oxford ISIS energy-dispersive system (EDS) with ultra-thin window detector. The EDS provided semi-quantitative chemical data that was reduced using the Oxford ISIS standardless software with the ZAF correction procedure selected. Analyses were performed on single, isolated structures, not on fibers that lay across other mineral particles. The operating conditions of the instrument were 15 kV, 0.5–3 nA (cup), and approximately 30% dead time. These conditions would excite an analysis volume of  $\sim 2 \mu\text{m}$ .

The matrix corrections used do not account for particle geometry. However, Small and Armstrong (2000) demonstrated that at 10–15 kV (utilized by this study) geometry-induced errors in the analyses of particles can be relatively small. One of the amphibole-rich study samples was analyzed by EDS and by electron probe microanalysis with wavelength dispersive spectroscopy (WDS) to evaluate the accuracy of the EDS measurements. Table 1 shows the comparison of analytical results by EDS and WDS. The amphibole nomenclature used in this study follows the recommendations of Leake and others (1997).

Samples for x-ray diffraction (XRD) analyses were pulverized and mechanically split. The minerals identified by XRD in the samples were categorized as major, minor, and trace mineral constituents of the analyzed split. “Major” minerals are estimated to comprise >25 wt% of the

**Table 1**

Comparison of the analyses of tremolite particles in one tremolite-rich specimen from the Death Valley region, as measured by two techniques: (1) energy dispersive x-ray analysis (EDS) on polished

and single unpolished grains, and (2) electron probe microanalysis with wavelength dispersive spectroscopy (WDS) on polished grains. Data are expressed in cation proportions, which were calculated by stoichiometry using 23 oxygen atoms

Mount type	Particle L x W ( $\mu\text{m}$ )	Analysis method	K	Na	Ca	Mn	Fe	Mg	Ti	Al	Si
Polished	203×106	WDS	0.01	0.06	1.88	0.01	0.04	4.93	bdl	0.03	7.99
		EDS	bdl	bdl	1.7	bdl	0.1	4.9	bdl	bdl	8.1
Polished	362×226	WDS	0.01	0.06	1.88	0.01	0.05	4.94	bdl	0.03	7.97
		EDS	bdl	bdl	1.7	bdl	bdl	5.0	bdl	bdl	8.1
Polished	620×228	WDS	0.01	0.06	1.87	0.02	0.06	4.90	bdl	0.03	8.00
		EDS	bdl	bdl	1.7	bdl	0.1	5.0	bdl	bdl	8.1
Polished	241×28.8	WDS	0.01	0.05	1.88	0.02	0.06	4.94	bdl	0.03	7.99
		EDS	bdl	bdl	1.8	bdl	bdl	4.9	bdl	bdl	8.1
Polished	140×14.3	WDS	0.01	0.05	1.85	0.02	0.06	4.93	bdl	0.04	8.00
		EDS	bdl	bdl	1.8	bdl	0.1	5.0	bdl	bdl	8.1
Loose	225×170	EDS	bdl	bdl	1.8	bdl	0.1	4.9	bdl	bdl	8.1
Loose	445×166	EDS	bdl	bdl	1.8	bdl	0.1	4.8	bdl	bdl	8.1
Loose	104×27.1	EDS	bdl	bdl	1.7	bdl	0.1	5.0	bdl	bdl	8.1
Loose	20.2×3.4	EDS	bdl	bdl	1.7	bdl	0.1	5.1	bdl	0.1	8.0
Loose	18.5×0.9	EDS	bdl	bdl	1.8	0.1	0.1	5.2	bdl	bdl	7.9
Loose	5.8×0.8	EDS	bdl	bdl	1.7	0.1	0.2	5.1	bdl	0.1	7.9
Loose	6.7×1.1	EDS	bdl	bdl	1.9	bdl	0.1	5.3	bdl	bdl	7.8
Loose	3.9×1.5	EDS	bdl	bdl	1.8	bdl	bdl	5.0	bdl	0.1	8.0
Loose	13.4×1.0	EDS	bdl	bdl	1.8	0.1	0.1	5.1	bdl	0.2	7.9

bdl, below the detection limit of the analytical technique

sample, “minor” minerals form 5–25 wt% of the sample, and “trace” minerals form <5 wt% of the sample. These estimates were based on the experience of the XRD operator with his instrumentation and its data output. The pulverized splits examined by this study provide snapshots of the mineralogy and variability in the talcose ores. However, quantitative estimates of the talc or amphibole content should not be interpreted from the XRD results shown in this report.

The XRD technique can identify the amphibole minerals within a sample as members of the tremolite-actinolite-ferroactinolite series, but is not able to determine the specific amphibole species. It is also not possible to positively distinguish between tremolite and the sodic-calcic amphiboles winchite and richterite by XRD.

## Amphibole-poor talc deposits formed by hydrothermal processes

### Geologic environments that host hydrothermal talc deposits

The term “hydrothermal” is commonly used in a general sense to describe the actions and products of hot fluids, often, but not always, implying an association with igneous processes. In this discussion, hydrothermal talc refers to deposits thought to be the products of fluids heated by a distant magma source, usually at depth. For example, in the Talc City district, California, no evidence of contact or regional metamorphism is apparent in the host or country rocks; the source of the heat that drove the talc-forming process is not obvious, and has been attributed to buried or distant igneous intrusions. Heat sources for the southwest Montana talc event(s) are speculated to be sills that intruded an overlying Proterozoic basin, heating and circulating basin brines towards underlying Archean marbles. Thus, “hydrothermal talc” refers to talc ore bodies that are not directly associated with regional metamorphism and are not found directly against an igneous intrusion.

The large, amphibole-poor, hydrothermal talc deposits of southwest Montana, Talc City, California, and west Texas, as examples, may represent the products of saline, siliceous fluids mobilized by basin-scale or localized magmatic activity. This genetic association is supported by the recent fluid-inclusion study by Gammons and Matt (2002) of the hydrothermal talc deposit currently excavated at the Yellowstone mine, southwest Montana, which indicated the presence of highly saline fluids during the talc formation. They proposed that “high heat flow, enhanced by injection of thick sills into the (Proterozoic) sedimentary pile, forced connate brines out of the bottom of the (Proterozoic) Basin and into the underlying or adjacent Precambrian basement, where they caused retrograde metamorphism and formation of economic talc and chlorite deposits” (replacing dolomitic marble and quartz-feldspathic gneiss, respectively) (Gammons and Matt 2002, p. 44).

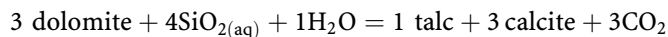
### Talc City district, California

The historical significance of the Talc City mining district in California from World War I through the 1940s is well documented by Page (1951). The district is in the Talc City Hills about 47 km southeast of Lone Pine, California. Page visited and sampled the district during its peak of production in the mid 1940s; the reader is referred to his report (Page 1951) for descriptions of the district’s geology, talc deposits, and mines. Gay and Wright (1954) completed a geologic map of the Talc City area. The talc deposits of the Talc City district are thick lenses and irregular masses hosted mainly by dolomite. To a much lesser extent talc bodies occur in “silica rock”, named by Page (1951) for an unstratified, massive rock composed mostly of interlocking quartz; it resembles quartzite in outcrop. Limestone is also nearby. Bedded dolomite is altered to massive dolomite adjacent to the talc deposits; both are often closely associated with silica rock. The silica rock is discontinuous at the mine sites, forming isolated lenses surrounded by massive dolomite. Silica rock appears to be partially replaced by talc at some of the deposits. Petrographic examination of the silica rock reveals microscopic patches of talc in interstitial areas between quartz grains (Page 1951).

Granitic bodies crop out from about 0.8 to 3.2 km distance from the mines. The granitic rocks locally have been hydrothermally altered, suggesting they were affected by the talc-forming hydrothermal event(s) and were not the source of fluids. Dikes ranging in composition from basalt to diorite to felsite crop out near the Talc City and Frisco mines (Page 1951). These dikes are also hydrothermally altered and interpreted to predate the talc alteration (Page 1951). A magmatic source of hydrothermal fluids is not obvious within the district. If buried, it may be best viewed by geophysical methods.

Page (1951) proposed a model for talc formation in the Talc City area that involved the following events:

1. The area was originally covered by mostly limestone, with lesser interbeds of dolomite, shale, and sandstone;
2. Hydrothermal fluids rich in Mg rose through and fractured the overlying limestones and altered them into massive dolomite, perhaps also converting sandstones to the “silica rock”;
3. A second event of fracturing accompanied another influx of hydrothermal waters enriched in Si and Mg, which replaced massive dolomite with large talc deposits and replaced silica rock with talc lenses. Page (1951) suggested the talc formed by the addition of silica and water to dolomite, and the addition of silica, water, and Mg to silica rock. This general reaction, shown below, is commonly invoked to explain the replacement of dolomite by talc:



Abundant fracturing and shearing of country rocks in the district suggest that fracture systems controlled and aided fluid flow and talc formation. Page’s interpretations are based on field relationships. However, by general

appearances, the talc deposits and associated rocks of the Talc City district do not display features typical of regional metamorphic processes, such as prominent foliation or compression structures.

The study sampled talc ore from pits or dumps at five sites in the Talc City district (Tables 2 and 3). No evidence of amphibole minerals was found in ore samples from this district based on x-ray diffraction (Table 2) and SEM-EDS analyses of the samples. Platy talc is mixed with small amounts of calcite, clinocllore, dolomite, quartz, kaolinite, vermiculite (uncertain identification) and K-feldspar (listed left to right in decreasing abundance). A friable white layer interlayered with the talc ore body at the Frisco mine consists of mostly quartz with accessory plagioclase, muscovite, dolomite, talc, and kaolinite. Thus, none of the descriptions of Page (1951), nor the results of our sampling and mineralogical analyses, indicate the presence of amphiboles in the talc deposits of the Talc City district.

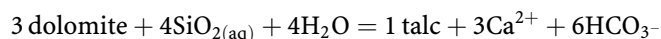
#### Yellowstone mine, southwest Montana

The Yellowstone talc mine is on the northeast flank of the Gravelly Range near Ennis, Montana. This enormous talc body (greater than 5.5 million short tons of known reserves) is the largest known in southwestern Montana, a region that contains a total of 57 talc mines, talc prospects, and known talc occurrences (Berg 1979; Van Gosen and others 1998). The Yellowstone mine is the largest talc-producer in the U.S., and two other large talc mines, the Regal and Treasure State mines, currently operate farther to the west in the Ruby Range. All three mines are open-pit operations.

All of the economically important talc deposits in the Ruby and Gravelly Range region of southwest Montana replaced dolomitic marbles of Archean age. In much smaller amounts, talc also replaced magnesite, quartz, tremolite, serpentine, and calcite, which are accessory constituents of the host marble (Berg 1979). Talc occurrences range from veinlets and pods centimeters thick up to huge masses, such as the thick talc body at the Yellowstone mine, which is at least 30 m thick (bottom not yet found). Most of the

southwest Montana talc bodies are lenticular and elongate, and in most places, talc lenses are parallel to the lithologic layering of the marble. However, talc bodies cut across layering at the Yellowstone mine (Cerino 2002).

The origin of the southwest Montana talc deposits is not completely understood, but recent work has reaffirmed earlier observations that the talc bodies appear to have formed during the Precambrian because they are restricted to Archean dolomitic marbles and do not replace overlying Cambrian dolomites. This observation was supported by a published age of 1.36 Ga by the  $^{40}\text{Ar}/^{39}\text{Ar}$  method for muscovite intergrown with talc in the Ruby Range (Brady and others 2003). A recent fluid inclusion study of the Yellowstone mine deposits (Gammons and Matt 2002, p. 44) determined that "the fluids responsible for talc formation were saline brines (roughly 7x saltier than modern seawater), and were enriched in  $\text{CaCl}_2$ ". They calculated burial depths during talc formation of more than 3 km at formation temperatures of 190 to 250 °C. Their model for talc formation at the Yellowstone mine site involves saline fluids that descended along growth faults in an overlying Proterozoic basin that may have existed above the Archean dolomitic marbles at about 1.36 Ga; they suggested the saline fluids were either supplied by connate brines in the basin sediments or by overlying seawater. Their model, as well as earlier models for talc formation in southwest Montana (Olson 1976; Anderson and others 1990; Brady and others 2003), invoke very large water to rock ratios to form these deposits, through the general reaction:



Anderson and others (1990) suggested that water to rock ratios of more than 600 are required by this reaction to carry sufficient silica in solution and flush most of the calcite out of the system.

Regardless of the source of the hydrothermal fluids or the circulation mechanism, the end result at the Yellowstone mine site is large bodies of mainly massive talc with light

**Table 2**

Mineral abundances in samples of hydrothermal talc ore collected from abandoned talc mines in the Talc City district near Lone Pine, California. The latitude and longitude values were measured by GPS using the North American Datum of 1927, CONUS. In regard to the x-ray diffraction results (see text), "major" minerals are estimated to comprise >25 wt% of the sample analyzed; "minor" minerals form 5–25 wt%; and "trace" minerals comprise <5 wt%

Site name, sample number	Latitude, longitude	Minerals identified by x-ray diffraction		
		Major	Minor	Trace
Talc City mine 11ADV02 11CDV03	36.3315, -117.6677	Talc Talc	Clinocllore, vermiculite(?)	Quartz, clinocllore Quartz, calcite
11FDV03 12ADV02 Silver Dollar mine	36.3371, -117.6617	Talc Talc, calcite		Kaolinite Dolomite, kaolinite
13ADV02 Alliance mine 14ADV02 14DDV03	36.3421, -117.6717	Calcite, talc Talc Talc, quartz	Clinocllore	Quartz, dolomite Quartz Vermiculite(?), kaolinite
Frisco mine 15ADV02 Viking mine 16ADV02	36.3303, -117.6800 36.3543, -117.7104	Clinocllore Talc		Talc, K-feldspar Clinocllore, quartz

green coloration, which contains trace amounts of limonite and goethite that replaced pyrite, along with traces of graphite. The light green color is attributed to 1%  $\text{Fe}^{2+}$  substituting for Mg in octahedral sites within the talc lattice (Cerino 2002). Minor substitution of  $\text{F}^-$  for  $\text{OH}^-$  is also noted. The bulk chemical compositions of talcose ores are shown in Table 3.

This study analyzed four samples of massive pale-green talc ore collected by the lead author from the floor of two open pits of the Yellowstone mine—two samples from an active pit and two from an inactive pit. XRD and SEM-EDS analyses of these samples revealed talc, with no other mineral impurities found. Late-stage (post-talc), large euhedral crystals of quartz and dolomite, accompanied by fine-grained Fe oxide minerals, commonly line cavities developed along faults that cut the talc bodies and country rock. These faults, which display normal displacements, are interpreted as growth faults (Cerino 2002) with intermittent movement through time. Magnesite is plentiful in the dolomitic marble that borders the talc deposits.

#### Allamoore district, west Texas

The ceramic-grade and paint-grade (higher purity) talc bodies currently being mined in the Allamoore district of west Texas were formed by the selective replacement of magnesite. Bourbon (1982, p. 77) suggested: “the [host] magnesite deposits were formed by chemical precipitation in isolated hypersaline lagoons or in associated ephemeral lakes.” Desiccation cracks and pseudomorphs of anhydrite and halite, preserved on bedding surfaces in the talcose intervals, indicate the hypersaline depositional environment of the host magnesite. Bourbon (1981, 1982) concluded that Allamoore talc formed via replacement of magnesite by hydrothermal connate or meteoric waters that carried silica in solution.

The Allamoore district presents a dilemma to the otherwise consistent relationships between geologic environment and amphibole content that are described in this paper. The talc bodies that are actively mined in the district are amphibole-free deposits. Yet, an undeveloped prospect on the edge of the district contains talc beds interlayered with long-fiber amphibole asbestos (potassium richterite to potassium winchite, Wylie and Huggins 1980). Microscopic studies of this asbestos deposit by Wylie and Huggins (1980) found that the ends of some of the asbestos fibers were altered to talc forming pseudomorphic fibrous talc, indicating the replacement of asbestos by talc. The amphibole asbestos in this prospect may represent an early fluid event driven by metamorphic processes. In contrast, the amphibole-free talc deposits that comprise the bulk of the district may have formed by a subsequent district-scale hydrothermal event, as suggested by Bourbon (1982). Basic igneous intrusions are exposed within a few talc deposits in the district (Bourbon 1981), perhaps sources of heat and convection for the talc-forming fluids.

#### Fluid inclusion studies of hydrothermal talc deposits

The geologic literature contains relatively few examples of fluid-inclusion research associated with large (commer-

cial) talc deposits. Especially sparse are fluid-inclusion studies of the major talc bodies in the U.S. Relevant published fluid inclusion data are primarily investigations of deposits described as “hydrothermal talc” that replaced dolostones or magnesite; most of these deposits lack amphibole. Examples are described below.

As noted earlier, analyses of fluid inclusions linked to the large talc deposits of the Ruby and Gravelly Ranges of southwest Montana were recently published. Gammons and Matt (2002) reported analyses and interpretation of fluid inclusions associated with the large talc bodies at the Yellowstone mine, Gravelly Range, Montana. They determined that the talc-forming fluids were brines at 190° to 250 °C containing about 10 wt% NaCl (2.2 m  $\text{Na}^+$ ), 11 wt%  $\text{CaCl}_2$ , and relatively low dissolved  $\text{CO}_2$ ; trapping pressures were estimated at 1–4 kbar. Brady and others (2003) examined the isotope geochemistry of muscovites and fluid inclusions in dolomite and calcite related to the formation of talc bodies in the nearby Ruby Range; they determined the metasomatic fluids were water-rich and  $\text{CO}_2$ -poor, and that the talc crystallized below  $\sim 350$  °C. Large, amphibole-deficient talc deposits at Rabenwald, eastern Alps of Austria, are thought to have formed by saline hydrothermal  $\text{SiO}_2$ -rich fluids that reacted with magnesite (Moine and others 1989). Fluid inclusions in quartz associated with the talc deposition show a wide range of salinities, with up to 32 wt% NaCl and 3.7 wt%  $\text{CaCl}_2$ ; analyses indicate that the inclusions were trapped at a minimum of 350 °C and 3 kbar vapor pressure (Pohl and Belocky 1999).

Talc deposits of Puebla de Lillo in northern Spain are replacement bodies in dolostones adjacent to quartzites. Fluid inclusion studies in dolomite and quartz related to the talc deposits, conducted by Tornos and Spiro (2000), suggest the talc-forming fluids were NaCl- $\text{CaCl}_2$ -rich brines at between 280° and 405 °C with variable salinities (0–23 wt% NaCl eq), under fluid pressures of only 165 to 450 bars. They attribute the dolomitization of pre-existing limestone here and the superimposed talc deposition to be the products of upwelling silica- and Mg-rich brines, heated and convected upward through extensional fault zones by igneous intrusions at depth.

The Mount Bischoff cassiterite-sulfide-rich skarn deposit in western Tasmania replaced a dolomitic horizon. The deposit contains a gangue assembly of quartz, talc, phlogopite, and carbonates. Halley and Walshe (1995) examined the fluid inclusions of this deposit and determined that the talc-bearing assemblage formed from hydrothermal fluids of 320° to 360 °C containing about 2 m NaCl and 1.5 m  $\text{CO}_2$ . They suggest that an Sn-enriched granite magma at  $\sim 1$ –2 km depth heated and convected the talc-forming fluids.

Several characteristics appear to be consistent within hydrothermal talc deposits, as evidenced by the fluid-inclusion studies described above. The common attributes of hydrothermal talc-forming fluids include: (1) high salinity contents typical of brines (high  $\text{Na}^+$  and  $\text{Ca}^+$ , low  $\text{CO}_2$ ); (2) temperatures below  $\sim 400$  °C; and (3) trapping pressures below  $\sim 4$  kbar. The studies described above each suggest that the source of heat and convection

**Table 3**

Major-element composition (wt%) of: (1) talc ores from the Yellowstone mine, southwest Montana; (2) talcose rocks of the Talc City district, California (Table 2); and (3) talcose rocks of talc-tremolite ore bodies of the southern Death Valley region, California (Tables 4 and 6). Analyses by wavelength-dispersive X-ray fluorescence spectrometry, conducted by Joseph E. Taggart, USGS laboratories in Lakewood, Colorado. See Taggart and others (1981, 1987) for descriptions of methods

Site/sample	Rock type	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	TiO <sub>2</sub>	P <sub>2</sub> O <sub>5</sub>	MnO	LOI
Yellowstone mine, southwest Montana												
02AYM02	Talc ore	61.9	<0.10	1.54	30.5	0.04	<0.15	<0.02	<0.02	<0.05	0.01	4.90
03AYM02	Talc ore	61.8	<0.10	1.44	30.4	0.08	<0.15	<0.02	0.02	<0.05	0.01	4.99
Talc City district, California												
Talc City mine												
11ADY02	Talc ore	61.6	0.62	1.19	30.5	0.12	<0.15	0.02	0.03	0.05	0.01	5.13
11CDY03	Talc ore	57.5	2.58	1.23	28.2	2.29	<0.15	<0.02	0.19	0.08	0.01	7.45
11FDY03	Talc ore	62.2	0.39	1.12	30.9	0.25	<0.15	<0.02	0.03	<0.05	0.01	5.14
12ADY02	Talc ore	44.6	0.45	0.51	23.2	14.7	<0.15	<0.02	0.03	<0.05	0.03	16.0
Silver Dollar mine												
13ADY02	Talc rock	33.5	4.76	0.36	22.1	18.1	<0.15	<0.02	0.13	0.06	0.02	20.4
Alliance mine												
14ADY02	Talc rock	63.1	0.21	0.59	30.7	0.05	<0.15	<0.02	0.03	0.05	<0.01	4.77
14DDY03	Talc rock	70.8	0.69	0.86	23.2	0.07	<0.15	<0.02	0.07	<0.05	0.01	3.99
Viking mine												
16ADY02	Talc rock	61.7	0.64	1.20	30.6	0.18	<0.15	<0.02	0.04	0.10	0.01	5.09
Southern Death Valley region, California												
Great Wanamingo mine												
07DDY02	Talc ore	54.9	0.52	1.07	26.4	5.95	<0.15	0.02	0.03	<0.05	0.08	9.84
09ADY02	Talc ore	58.9	0.37	0.79	27.6	6.15	<0.15	0.09	0.03	<0.05	0.06	3.73
Grantham mine												
21CDY03	Talc ore	52.2	0.23	0.22	25.9	9.13	0.32	0.20	0.05	<0.05	0.01	11.0
21FDY03	Talc rock	27.6	0.81	0.82	11.9	31.1	0.69	0.49	0.07	<0.05	0.11	26.0
Number 3 workings												
23DDY03	Talc ore	62.1	0.32	0.20	30.9	1.20	<0.15	0.09	0.03	<0.05	0.01	4.67
White Point workings												
23EDY03	Talc ore	54.7	0.35	0.25	26.3	9.48	0.78	0.37	0.04	<0.05	0.02	6.79
23FDY03	Talc ore	56.2	0.44	0.32	27.1	6.98	0.94	0.45	0.05	<0.05	0.02	7.17
Moorehouse mine												
30CDY03	Talc rock	37.2	0.69	0.31	19.0	21.5	<0.15	0.67	0.02	<0.05	0.08	19.7
30DDY03	Talc ore	54.9	0.26	0.23	27.8	6.40	<0.15	0.27	0.03	<0.05	0.03	9.39
30EDY03	Talc schist	42.1	3.80	1.19	20.9	13.1	1.59	3.96	0.10	<0.05	0.05	12.7
30GDY03	Talc ore	57.0	0.73	0.71	25.4	4.92	3.63	1.74	0.05	<0.05	0.02	5.11
Pleasanton mine												
36BDY03	Talc ore	50.9	0.61	0.36	24.0	7.76	<0.15	0.52	0.04	<0.05	0.01	15.0
36DDY03	Talc ore	51.7	0.41	0.37	24.9	10.7	0.91	0.59	0.05	<0.05	0.04	9.89
36EDY03	Talc ore	49.8	0.48	0.29	19.9	10.4	<0.15	0.31	0.03	<0.05	0.02	18.1
Acme mine												
24CDY02	Talc ore	60.3	0.57	0.38	28.4	3.51	0.72	0.32	0.08	<0.05	0.02	4.67
25BDY02	Talc ore	44.8	1.20	0.46	25.0	9.98	0.59	0.93	0.06	<0.05	0.03	16.1
27BDY03	Talc ore	53.9	0.31	0.29	24.6	11.4	0.58	0.24	0.04	<0.05	0.02	7.84
27CDY03	Talc ore	49.8	1.26	1.32	23.2	11.3	1.85	1.09	0.07	<0.05	0.04	8.98
27EDY03	Talc ore	56.9	0.72	0.61	24.9	9.41	2.59	0.43	0.06	0.06	0.03	3.15
27FDY03	Talc ore	55.0	0.51	0.37	25.3	10.5	1.83	0.31	0.05	<0.05	0.03	5.40
Kingston Range												
28ADY02	Talc rock	58.7	0.17	2.95	26.2	6.33	<0.15	0.02	0.07	0.05	0.08	4.30
29ADY02	Talc ore	57.1	0.44	0.34	24.9	11.5	<0.15	0.21	0.05	<0.05	0.03	3.77

LOI, loss-on-ignition; total Fe calculated as Fe<sub>2</sub>O<sub>3</sub>



**Table 4**

Names and locations of talc-tremolite deposits sampled by this study within the southern Death Valley region, California. The deposits replaced dolostones along their contacts with intruding mafic sills.

The references cited provide descriptions of geology and historic production at these sites, as well as for similar mines and prospects in these areas. The latitude and longitude values were measured by GPS using the North American Datum of 1927, CONUS

District, site name	Latitude, longitude	References
Yucca Grove district		
Great Wanamingo mine	35.4268, -115.8498	Wright and others (1953)
Warm Spring Canyon, Death Valley National Park		
Grantham mine (Big Talc)	35.9611, -116.8955	Wright (1957; 1968); Norman and Stewart (1951); Franklin (1965); Papke (1975b);
Number 3 workings	35.9663, -116.9213	Evans and others (1976)
White Point workings	35.9684, -116.9283	
Ibex Hills, Death Valley National Park		
Monarch mine	35.7767, -116.4083	Wright (1957; 1968); Wright and others (1953); Evans and others (1976)
Moorehouse (Ibex) mine	35.7802, -116.4160	
Pleasanton mine	35.7775, -116.4110	
Alexander Hills, near Tecopa		
Acme mine	35.7682, -116.1275	Wright (1957; 1968); Wright and others (1953)
Kingston Range		
Talcose outcrop	35.7842, -115.9290	Wright (1957; 1968); Wright and others (1953)
Abandoned talc ore pile	35.7900, -116.0000	

that warmed and circulated the talc-forming brines was a buried igneous mass (or masses) with localized hydrothermal fluid circulation assisted by extensional faults that served as fluid conduits. Note that another consistent characteristic of the hydrothermal talc deposits is the absence of amphiboles in the talc ore bodies or wall rocks. In contrast, amphiboles are found to coexist with talc in deposits that formed in higher temperature systems. For example, a fluid-inclusion study was conducted on metasomatic tremolite-talc vein deposits at Campolungo, Switzerland. Here, Walther (1983) analyzed fluid inclusions within thin reaction zones (4 cm in width) between vein quartz and dolomite; the zones contain calcite + tremolite + phlogopite + talc. Walther (1983) determined that the metasomatic fluids were at 500 °C, had an approximate composition of ~5 wt% NaCl and 0.5 mole fraction CO<sub>2</sub>, and were emplaced at ~3.25 kbar. A fluid-inclusion study was also performed on the Dongyang talc deposit in Korea by Park and others (1997). They determined that an early event of talc-tremolite replacement of dolomite was due to fluids of ~440–480 °C under ~1.64–2.53 kbar pressure, while a subsequent event of talc deposition that lacked tremolite was due to fluids of ~360–390 °C under pressures of ~1.4–2.2 kbar. Based on the results of the fluid-inclusion studies described above, it appears that the temperature of ore-forming fluids was an important factor in the presence or absence of amphibole crystallization in the talc bodies. Specifically, talc deposits that formed from fluids of less than ~400 °C, typical of hydrothermal systems, share a distinct absence of accessory amphibole minerals. In contrast, talc deposits formed in higher temperature environments, typical of contact and regional metamorphic settings, consistently contain amphiboles. However, attributing the control on amphibole crystallization to simply the temperature of the fluids may be an oversimplification of these complex ore-forming systems, as is discussed at the end of this paper.

## Amphibole-rich talc deposits formed by contact metamorphism

Talc bodies categorized herein as “contact metamorphism” types refer specifically to deposits found in direct contact with an igneous body that are thought to have formed by metasomatism due to the emplacement of that igneous body.

### Death Valley region, California

Probably the best examples of talc ore bodies formed within a geologic setting of contact metamorphism are 55 deposits mined and prospected in the southern Death Valley region of California. The mines, most now inactive and (or) abandoned, are clustered in widely separated but discrete districts. Samples were collected from ten of these deposits (Table 4).

The Yucca Grove district, about 29 km northeast of Baker, California, comprises four groups of mines that extracted talc-tremolite rock (Wright and others 1953). The largest operation was the Great Wanamingo mine, consisting of several open-pit workings. The deposits are lens-shaped bodies of massive talc-tremolite rock bounded by a greenish calc-silicate hornfels. Mafic dikes and granitic pegmatites (less than 1 ft thick) also bound the ore zone (chemical compositions shown in Table 5). Thin layers composed of phlogopite, muscovite, and clinocllore formed along the contacts of granitic pegmatites with talc ore. The talc bodies apparently replaced carbonate intervals of a Precambrian-age metasedimentary sequence (Wright and others 1953).

Three samples of friable, massive, white ore material were collected from pit walls of the Great Wanamingo mine, and later analyzed by XRD and SEM/EDS. The samples of ore material contained talc and tremolite, with talc content apparently exceeding tremolite content, and accessory calcite, dolomite, clinocllore, quartz, sepiolite, and kaolinite (Table 6). Asbestiform fibers, with compositions

**Table 5** Major-element composition (wt%) of intrusive and dolomitic host rocks associated with talc-tremolite ore bodies of the southern Death Valley region, California (Table 4). Analyses by wavelength-dispersive X-ray fluorescence spectrometry, conducted by Joseph E. Taggart, USGS laboratories in Lakewood, Colorado. See Taggart and others (1981, 1987) for descriptions of methods

Site/sample	Rock type	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	TiO <sub>2</sub>	P <sub>2</sub> O <sub>5</sub>	MnO	LOI
Southern Death Valley region, California												
Great Wanamingo mine												
07ADV02	Mafic dike	55.5	17.6	8.09	3.16	1.01	2.26	8.71	0.87	0.16	0.07	1.78
07BDV02	Granite dike	70.9	14.4	2.58	1.53	2.88	3.90	1.56	0.45	0.13	0.03	1.36
Grantham mine												
21ADV03	Dol. ls	38.4	8.49	1.81	3.86	21.4	0.77	7.32	0.18	<0.05	0.03	17.3
22ADV03	Gabbro sill	43.2	16.3	15.8	6.17	6.21	3.41	1.02	3.41	0.47	0.18	3.03
21GDV03	Gabbro sill	45.6	14.0	16.2	5.29	4.94	4.63	0.49	4.20	0.71	0.26	3.19
White Point workings												
23GDV03	Gabbro sill	49.6	13.5	13.6	4.24	7.14	5.33	0.40	2.74	1.51	0.24	1.04
Moorehouse mine												
31ADV03	Gabbro sill	43.8	13.4	15.3	8.72	6.51	2.72	1.00	2.20	0.37	0.20	5.20
Pleasanton mine												
36ADV03	Gabbro sill	47.6	14.5	15.2	4.55	6.34	2.39	3.28	2.92	0.57	0.20	2.05
Acme mine												
26BDV02	Dol. ls	57.0	0.21	1.27	8.33	12.7	<0.15	0.10	0.03	<0.05	0.06	19.6
24ADV02	Gabbro sill	45.6	14.7	15.5	6.47	2.69	4.24	3.07	3.72	0.69	0.22	2.70
27DDV03	Gabbro sill	39.5	13.0	14.4	10.6	3.78	2.10	5.82	3.91	0.67	0.14	2.54

LOI, loss-on-ignition; total Fe calculated as Fe<sub>2</sub>O<sub>3</sub>

compatible with tremolite (by EDS analyses), were found in one of the talc samples (Tables 6 and 7), but were widely scattered.

The Silver Lake mining district consisted of eight talc mines (Wright 1954) about 20 km north-northeast of Baker. Although these were deemed “talc” mines, Wright (1954, p. 13) noted: “tremolite forms an estimated three-fourths of the volume of the bodies.” Talc is the next largest ore-body component. The tremolite-talc bodies are hosted by a diopside-feldspar-quartz-calcite hornfels unit, part of a metasedimentary rock sequence thought to be Precambrian in age. The tremolite-talc rock and the hornfels are interpreted to have replaced carbonate rock. Wright (1954) estimated that the mineable bodies range from about 10 to 240 m long and from 1.5 to 4.5 m wide. Wright related the contact metamorphism to the emplacement of large bodies of granitic rocks found near the tremolite-talc bodies. Thin mafic dikes are also found near the borders of several ore zones. Thin laminae of mostly phlogopite are interlayered with the ore body; these laminae often form a selvage along the ore-hornfels contact.

The other 43 tremolite-talc mines of the region lie in mountain ranges that surround the southern half of Death Valley National Park; the talc-bearing belt is about 120 km long by 24 km wide. The geology of the region, the mine sites, and their early mining history are well described by Wright (1968). These deposits are geologically rather similar across the region (Wright 1957, 1968; Evans and others 1976). Thick mafic (gabbroic) sills (Table 5), mostly medium-grained, intruded a siliceous (cherty) dolomitic member of the Proterozoic-age Crystal Spring Formation, forming friable tremolite-talc-rich rock along the sill-carbonate contact zones. The gabbro sills were emplaced during the Mesoproterozoic, based on age determinations by the U-Pb method from baddeleyite crystals in two sills (1,087 ± 3 and 1,069 ± 3 Ma, Heaman and Grotzinger 1992). The consistent stratigraphic position of the sills at or near the base of the carbonate horizon of the Crystal Spring Formation, but not higher, suggests the sills were emplaced before deposition of the overlying rocks and also indicates that the talc-tremolite deposits are Mesoproterozoic in age.

The tremolite-talc replacement bodies are typically from 150 up to 1,500 m long and 3 to about 30 m thick. The deposits locally contain more tremolite than talc, or more talc than tremolite. SEM observations of the ore material suggest that the tremolite and talc formed by coeval crystallization. Most commonly, acicular amphiboles and platy talc occur intergrown on a microscopic scale (Fig. 1), with only sporadic evidence of talc replacing amphibole.

The largest talc-tremolite mining district of the Death Valley area, and likely the largest producer, was the Grantham-Warm Spring district, which consisted of a series of adits and open pits spread out for just over 3.2 km along Warm Spring Canyon in southwestern Death Valley National Park (Franklin 1965; Wright 1968; Papke 1975b). The second largest mine complex, consisting of adits and large open pits, was the Western-Acme

**Table 6**

Analyses of talcose samples from talc mines, dumps, and outcrop in the southern Death Valley region, California (see Table 4). For the x-ray diffraction results (see text), “major” minerals are estimated to comprise >25 wt% of the sample analyzed; “minor” minerals form 5–25 wt%; and “trace” minerals comprise <5 wt%

Site name, Sample number	Minerals identified by x-ray diffraction			Amphibole fibers by SEM/ EDS
	Major	Minor	Trace	
Great Wanamingo mine 07DDV02	Talc		Dol, cal, qtz, amph, sep, kaol	Extremely rare
08ADV02	Talc	Cal, amph	Clino, sep, qtz	None were found
09ADV02	Talc	Amph	Cal, qtz, kaol	None were found
Grantham mine				
20ADV03	Talc	Cal	Amph, qtz, phl	Trace
21BDV03	Talc, qtz	Cal	Amph, sep	Trace
21CDV03	Talc	Cal	Amph, vrm	Extremely rare
21FDV03	Cal, talc		Amph, mus, phl, qtz	Trace
Number 3 workings				
23DDV03	Talc		Amph, vrm	Trace
White Point workings				
23ADV03	Talc		Amph, phl, cal, dol	Trace
23BDV03	Talc	Amph	Phl, cal, dol, qtz, sap	Trace
23CDV03	Talc	Amph, cal	Phl, dol, qtz, sap	Trace
23EDV03	Amph, talc	Dol	Mus, qtz, cal, vrm	Trace
23FDV03	Talc	Amph	Qtz, cal, vrm, ant, dol, mus	Extremely rare
Monarch mine				
30ADV03	Talc	Amph, cal	Phl	Trace
30BDV03	Talc		cal, qtz, dol, amph, phl	Trace
Moorehouse (Ibex) mine				
30CDV03	Cal, talc		Mus, amph	Trace
30DDV03	Talc	Cal	Mus, qtz, phl	Trace
30EDV03	Cal, phl	Amph, talc		Trace
30GDV03	Talc, amph		Qtz, dol, mus, cal	Trace
31BDV03	Talc, dol	Phl		Trace
31CDV03	Talc, dol, cal		Amph, phl, sep	Trace
Pleasanton mine				
36BDV03	Talc, dol	Qtz	Mus	Extremely rare
36DDV03	Talc, cal	Amph, mgh	Dol, mus(?)	Extremely rare
36EDV03	Qtz, dol, talc		mus	Trace
Alexander Hills				
24CDV02	Talc		Amph, cal, phl	Trace
24DDV02	Talc, dol	Cal, amph	Phl	Trace
25ADV02	Cal	Talc	Amph, phl	Trace
25BDV02	Talc	Cal, dol, sep	Phl, amph	Extremely rare
26ADV02	Talc	Cal	Amph, phl	Trace
27BDV03	Amph, mgh	Talc, dol	Cal	Trace
27CDV03	Amph, talc, mgh	Qtz, dol	Ant	Extremely rare
27EDV03	Amph, mgh		Talc, cal, mus, ant	Extremely rare
27FDV03	Amph	Talc	Ant, cl-chry, dol, cal	Trace
Kingston Range				
28ADV02	Amph	Talc	Cal, kaol(?)	Trace
28BDV02	Qtz	Amph, talc		Trace
29ADV02	Talc, amph, cal		Qtz, k-spar	Trace

Mineral abbreviations: dol, dolomite; cal, calcite; qtz, quartz; amph, amphibole of the tremolite-actinolite series; sep, sepiolite; kaol, kaolinite; clino, clinocllore; sap, saponite; mgh, ferroan magnesiohornblende; ant, antigorite; k-spar, K-feldspar; mus, muscovite; phl, phlogopite; vrm, vermiculite; cl-chry, clinochrysotile (best fit identification by mineral structure). Fibrous amphibole particles were

identified by visual scans of the sample by SEM and analyses of the particle by EDS (see text); asbestiform amphiboles were described as “trace” in occurrence (a number of fibers, up to 1% by volume but usually less), “extremely rare” (a few fibers found, widely scattered), or “none were found”

mine in the Alexander Hills southeast of Tecopa (Wright 1968).

Samples of talcose rock were collected from abandoned mines, dumps, and outcrops in the southern Death Valley area (Tables 3, 4, and 6). The samples suggest talc is the predominant ore mineral; however, as noted in earlier publications, tremolite is typically a major constituent of

these deposits (Fig. 1, Tables 6 and 7). Other major to minor components of the ore material include calcite, dolomite, quartz, phlogopite, magnesiohornblende, and sepiolite (Table 6).

The tremolite particles in the Death Valley ores, as is typical in tremolitic talc deposits, range in habit from blocky to prismatic to acicular to asbestiform, commonly



**Fig. 1**

SEM photomicrograph of a bundle of fibrous tremolite mixed with talc platelets in talc-tremolite ore material from the White Point mine (Table 4), Warm Spring Canyon, Death Valley National Park, California. (Sample 23ADV03, Tables 6 and 7)

within a single sample. Scattered amphiboles in the Death Valley talc deposits occur in asbestiform habits, as bundles of fibers (Figs. 1 and 2) and loose fibers (Figs. 3 and 4). Using SEM/EDS, examination of talc ore samples from the southern Death Valley mines found asbestiform amphiboles in most of the samples. Whereas amphibole particles with prismatic to acicular habits were most common, particles with asbestiform habit (less than 1  $\mu\text{m}$  in diameter, 10  $\mu\text{m}$  and greater in length, curved, splayed ends; Virta 2001) were locally numerous.

In addition to the previously recognized tremolite, EDS analyses indicated that a number of the asbestiform particles in talc ore collected from several mines (Figs. 2, 3, 4, Table 7) have compositions consistent with the sodic-calcic amphiboles richterite and winchite (Leake and others 1997; Wylie and Verkouteren 2000).

A quantitative assessment of the “asbestos” content in the Death Valley talc ores was beyond the scope of this study. The study’s SEM/EDS analysis of the mineral residues caused by light handling of the ore samples suggests that prismatic particles are the most common amphibole habit in the talcose rocks. Blocky, prismatic, and acicular examples of the amphiboles in each sample yielded compositions similar to those measured in the fibrous particles (representative fiber compositions shown in Table 7). No obvious correlation between particle composition and morphology was found—tremolite, richterite, and winchite compositions were found in crystals that range from non-fibrous to highly fibrous in habit.

It should be emphasized that the sampling and SEM/EDS studies of these talc deposits were reconnaissance in fashion. Importantly, asbestiform amphiboles in the ore samples were often encountered in SEM scans of the ore material; asbestiform particles locally occur in amounts as high as one percent (by volume), but typically less, in ore samples (described as “trace” in Table 6).

### North Carolina deposits

Other examples of talc-amphibole deposits that formed within geologic environments of contact metamorphism occur in western North Carolina; these relatively small talc deposits are spatially and genetically associated with the Day Book dunite body (Murdock and Hunter 1946). Where pegmatites intruded the dunite body, the reaction of magnesian olivine in the dunite with silica in solution formed contact aureoles, which are a several centimeters to a couple of meters thick. The alteration haloes that bound the contacts of pegmatite with dunite contain zones of talc, anthophyllite asbestos, and phlogopite (weathered to vermiculite near the surface) in a serpentine-rich groundmass (Kulp and Brobst 1954).

### Talc-amphibole formation in conditions of contact metamorphism

The talc-tremolite deposits of the southern Death Valley-Kingston Range region of California (Wright 1968) were clearly formed by metasomatism caused by intruding gabbro sills. The study samples from inactive talc mines of this region (Tables 3, 4, 5, 6, and 7) represent aspects of these deposits.

Fluid inclusion analyses of the southern Death Valley talc-tremolite deposits have not been performed, so the genetic model presented here is speculative. Wright (1968) determined through field relations that the gabbroic sills intruded the lower and basal horizons of the carbonate section of the late Precambrian Crystal Spring Formation before much of the overlying strata were deposited; he estimated that the overlying sediment load during sill emplacement is now represented by 60 to 760 m of overlying metasedimentary rock. Wright (1968) also suggested that during sill intrusion, the limy strata (now siliceous dolomitic limestone) were poorly consolidated and saturated with water from an overlying sea. Thus, during sill emplacement (and corresponding talc-tremolite deposition) the pore fluids were likely as saline as connate seawater or perhaps more saline. The constituents required to form talc and calcic amphiboles— $\text{Si}^{4+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Ca}^{2+}$ , and  $\text{H}_2\text{O}$ —were locally abundant within the contact metamorphic environments associated with the southern Death Valley deposits. A migration of heated silica-rich waters through cherty, dolomitic sediments or rock can explain the coexisting talc-tremolite intergrowths that are common within the Death Valley deposits (Fig. 1). Silica saturation is evidenced by the silicification of the dolomitic limestones that overlie the tremolite-talc deposits (samples 21ADV03 and 26BDV02, Table 5). The gabbroic sills provide an obvious source for the heat and additional silica required to drive these reactions.

### Amphibole-rich talc deposits formed by regional metamorphism

#### Gouverneur district, upper New York State

Talc has been mined for more than a century in the Gouverneur mining district in the western part of

**Table 7**  
Representative cation proportions of fibrous amphibole and platy talc particles as calculated from SEM/EDS analyses of samples from talc-tremolite deposits of the southern Death Valley region, California

Site, Sample no	Fiber shape L x W (µm)	Probable amphibole	Amphibole particle							Talc particle						
			K	Na	Ca	Mn	Fe	Mg	Ti	Al	Si	Mg	Fe	Si		
Great Wamamingo mine 07DDV02	33.5×1.2	Tremolite	bdl	bdl	1.7	bdl	bdl	0.1	5.2	bdl	bdl	bdl	8.0	3.0	bdl	4.0
Grantham mine 20ADV03	17.6×0.9	Winchite	0.4	1.0	1.0	bdl	bdl	0.2	4.7	bdl	bdl	bdl	8.1	3.0	bdl	4.0
21BDV03	21.4×0.7	Richterite	0.3	1.4	0.8	bdl	bdl	0.3	4.8	bdl	bdl	bdl	8.0	2.9	bdl	4.0
21CDV03	17.3×1.3	Winchite	0.2	0.7	1.3	bdl	bdl	bdl	5.1	bdl	bdl	bdl	8.1	2.7	bdl	4.1
21FDV03	60.3×0.5	Richterite	0.1	1.9	0.9	bdl	bdl	0.3	5.1	bdl	bdl	bdl	7.8	2.9	bdl	4.0
Number 3 workings 23DDV03	22.5×1.5	Tremolite	bdl	bdl	1.8	bdl	bdl	0.1	5.0	bdl	bdl	bdl	8.1	3.0	bdl	4.0
White Point workings 23ADV03	No data	Tremolite	bdl	bdl	1.9	bdl	bdl	bdl	4.9	bdl	bdl	bdl	8.0	3.0	bdl	4.0
23BDV03	56.3×3.4	Tremolite	0.1	0.2	1.6	bdl	bdl	bdl	4.9	bdl	bdl	bdl	8.2	3.1	bdl	3.9
23CDV03	20.5×1.0	Tremolite	bdl	0.2	1.5	bdl	bdl	0.1	5.3	bdl	0.1	bdl	7.9	3.0	bdl	4.0
23EDV03	26.2×0.9	Tremolite	bdl	0.2	1.6	bdl	bdl	bdl	5.2	bdl	bdl	bdl	8.0	3.0	bdl	4.0
23FDV03	9.0×0.6	Winchite	0.1	0.7	1.3	0.1	bdl	0.1	5.0	bdl	bdl	bdl	8.0	3.0	bdl	4.0
Monarch mine 30ADV03	12.3×0.7	Winchite	0.3	1.1	0.9	bdl	bdl	0.6	4.5	bdl	bdl	bdl	8.1	2.9	bdl	4.0
30BDV03	75.3×2.3	Winchite	0.2	0.9	1.2	bdl	bdl	0.2	4.9	bdl	bdl	bdl	8.0	2.8	bdl	4.1
Moorehouse mine 30CDV03	25.2×1.8	Richterite	0.3	1.4	1.0	bdl	bdl	0.3	4.9	bdl	bdl	bdl	8.0	2.9	bdl	4.0
30DDV03	31.6×1.4	Richterite	0.3	1.9	0.7	bdl	bdl	0.2	5.1	bdl	bdl	bdl	7.9	2.9	bdl	4.0
30EDV03	60.5×2.0	Winchite	0.4	1.2	0.8	bdl	bdl	0.2	5.0	bdl	bdl	bdl	7.9	2.9	bdl	4.0
30GDV03	44.8×1.6	Richterite	0.1	1.8	0.8	bdl	bdl	bdl	5.2	bdl	bdl	bdl	8.0	3.1	bdl	4.0
31BDV03	18.4×0.8	Tremolite	0.1	0.1	1.7	bdl	bdl	0.1	5.1	bdl	bdl	bdl	8.0	2.9	bdl	4.0
31CDV03	56.7×1.3	Tremolite	0.1	0.2	1.7	bdl	bdl	bdl	5.1	bdl	bdl	bdl	8.0	2.9	bdl	4.1
Pleasanton mine 36BDV03	29.9×0.5	Richterite	0.1	2.0	0.6	0.1	bdl	0.2	5.0	bdl	bdl	bdl	7.9	2.9	bdl	4.0
36DDV03	26.4×0.4	Winchite	0.2	1.6	0.6	bdl	bdl	0.2	5.2	bdl	bdl	bdl	7.9	2.9	bdl	4.1
36EDV03	34.8×1.6	Richterite	0.2	1.9	0.6	bdl	bdl	0.1	5.0	bdl	bdl	bdl	8.1	2.8	bdl	4.1
Alexander Hills 24CDV02	22.0×0.8	Tremolite	0.1	0.3	1.6	bdl	bdl	bdl	5.1	bdl	bdl	bdl	8.0	2.9	bdl	4.0
24DDV02	24.5×0.9	Richterite	0.1	2.1	0.5	bdl	bdl	0.2	5.1	bdl	bdl	bdl	7.9	2.9	bdl	4.1
25ADV02	22.4×1.6	Winchite	0.3	0.9	1.0	bdl	bdl	0.1	5.1	bdl	bdl	bdl	8.1	2.9	bdl	4.1
26ADV02	12.9×1.3	Richterite	0.4	1.6	0.9	bdl	bdl	0.1	5.2	bdl	bdl	bdl	7.9	3.0	bdl	4.0
27BDV03	59.0×0.7	Tremolite	bdl	bdl	1.7	bdl	bdl	0.2	5.1	bdl	bdl	bdl	8.0	3.0	bdl	4.0
27CDV03	20.3×0.7	Tremolite	bdl	bdl	1.8	bdl	bdl	0.4	5.1	bdl	bdl	bdl	7.8	3.0	bdl	4.0
27EDV03	24.1×1.0	Tremolite	0.1	0.1	1.9	bdl	bdl	0.1	5.1	bdl	bdl	bdl	7.9	3.0	bdl	4.0
27FDV03	19.6×1.2	Tremolite	0.1	0.2	1.6	bdl	bdl	0.1	5.0	bdl	bdl	bdl	8.0	3.0	bdl	4.0
27FDV03	15.9 x 0.7	Tremolite	bdl	bdl	1.8	bdl	bdl	0.1	5.1	bdl	0.1	bdl	7.9	3.0	bdl	4.0
Kingston Range 28ADV02	20.3×1.1	Tremolite	bdl	bdl	1.8	bdl	bdl	0.3	5.0	bdl	bdl	bdl	8.0	2.9	0.1	4.0

Table 7 (Contd.)

Site, Sample no	Fiber shape L x W ( $\mu\text{m}$ )	Probable amphibole	Amphibole particle							Talc particle					
			K	Na	Ca	Mn	Fe	Mg	Ti	Al	Si	Mg	Fe	Si	
28BDV02	92.0x1.4	Tremolite	0.1	0.2	1.7	bdl	0.1	4.9	bdl	bdl	bdl	8.1	2.9	0.1	4.0
29ADV02	22.9x1.6	Winchite	0.2	0.6	1.4	bdl	bdl	4.9	bdl	bdl	bdl	8.1	3.1	bdl	3.9

Sample localities are listed in Table 4. Cation ratios were calculated by stoichiometry using 23 oxygen atoms for amphibole and 11 oxygen atoms for talc. (OH) was assumed to be 2 for amphiboles and talc. The EDS technique cannot distinguish between the oxidation states of Fe ( $\text{Fe}^{3+}$  versus  $\text{Fe}^{2+}$ ). Most of the amphibole analyzed in this study had negligible Fe; therefore, the oxidation state of Fe would not greatly affect the compositional calculations. Amphiboles are identified as the most likely amphibole species based on semi-quantitative results. Amphibole nomenclature used is based on the recommendations of Leake and others (1997). bdl, below the detection limit of the EDS analytical method



Fig. 2

SEM photomicrograph of a fibrous amphibole bundle (likely richterite) in talc ore material from the Grantham mine (Table 4), Death Valley National Park. Sample collected just inside the ore body within a couple of inches of its outer contact with dolomitic limestone country rock. (Sample 21BDV03, Tables 6 and 7)

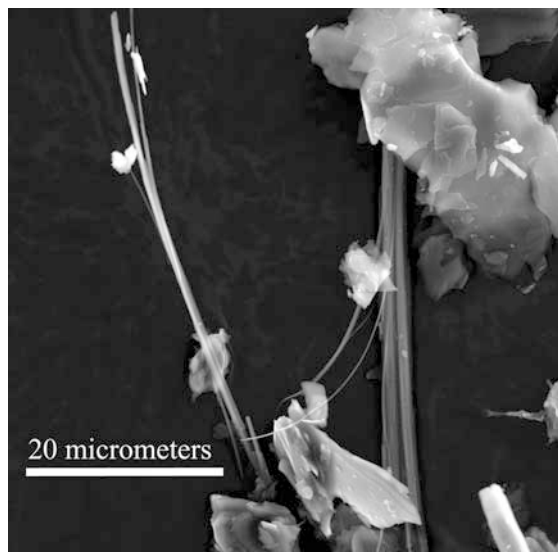
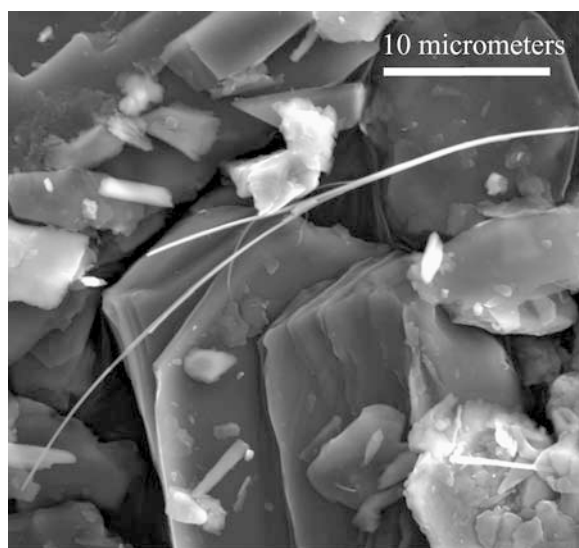


Fig. 3

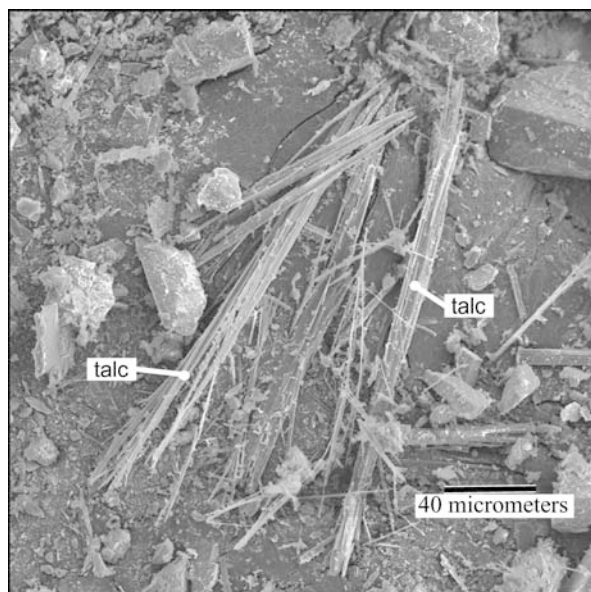
SEM photomicrograph of asbestiform richterite (?) and platy talc in ore material from the Grantham mine (Table 4), Death Valley National Park. (Sample 21BDV03, Tables 6 and 7)

north-central New York State. These talc deposits replaced dolomitic marble in sinuous belts several kilometers long. The talc-forming event in the district has been interpreted to represent late retrograde metasomatism accompanying significant fluid flow during waning stages of regional metamorphism (Engel 1962). The talcs of the Gouverneur district are often cited as an example of "fibrous talc." Fibrous talc describes talc-rich rocks consisting of an intergrowth of acicular talc (Fig. 5) and



**Fig. 4**

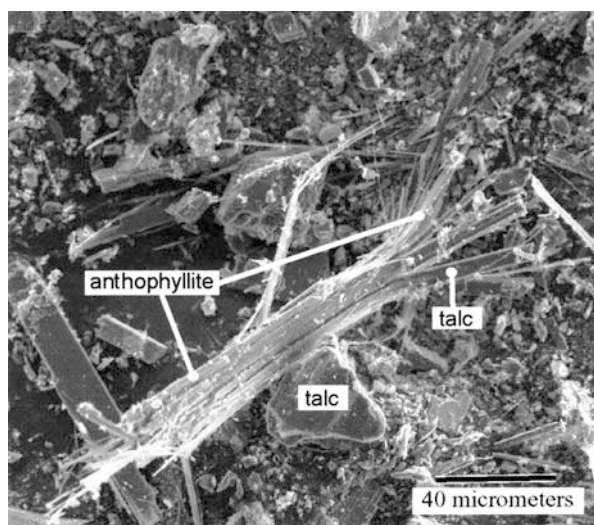
SEM photomicrograph of platy talc with asbestiform amphibole (winchite?). Coexisting talc and fibrous amphibole are common in the talc deposits formed by contact metamorphism in the southern Death Valley region. This example is from the ore zone of the Acme mine (Table 4) near Tecopa, California (sample 26ADV02, Tables 6 and 7)



**Fig. 5**

SEM photomicrograph of fibrous talc within a talc deposit formed by regional metamorphism. This example is from the Gouverneur mining district, north-central New York State. Refer to Table 8 for semi-quantitative (EDS) analyses of these fibers

acicular amphiboles (Goodwin 1974; Greenwood 1998), and commonly includes the pseudomorphous replacement of fibrous amphiboles by talc (Fig. 6); this lends the talcose rock a generally fibrous, rather than massive appearance. The amphiboles intergrown with talc in the Gouverneur deposits are widely but unevenly distributed tremolite and anthophyllite (Engel 1962; Ross and others 1968; Virta 1985; Greenwood 1998). Mn-cummingtonite



**Fig. 6**

Example of a “transitional” particle found within a talc deposit formed by regional metamorphism. The particle displays the incomplete replacement of fibrous anthophyllite by talc. This example is from the Gouverneur mining district, north-central New York State. The mineral compositions and identified phases based on stoichiometry at the spots indicated in this SEM photomicrograph were determined by EDS analyses, as shown in Table 8

(“tirodite”) is also reported (Ross and others 1968). Overlapping mineral crystallization events, linked to stages of regional metamorphism, are evident in the Gouverneur deposits. The general paragenetic sequence has been determined to involve: (1) formation of acicular tremolite (the primary metamorphic mineral) followed by (2) local replacement by pseudomorphous anthophyllite, followed, during the last stages of regional metamorphism, by (3) replacement of tremolite and anthophyllite by fibrous talc and serpentine (Engel 1962; Ross and others 1968). The resulting deposits consist of fibrous to platy talc, and tremolite, anthophyllite, and minor Mn-cummingtonite in habits ranging from blocky to fibrous. Some amphiboles in the Gouverneur talc ores have been described as “fibrous”. When these mineral particles are characterized as asbestos or asbestiform, however, it has led to much debate (Goodwin 1974; Occupational Safety and Health Administration 1992). Much of this controversy is due to inconsistent classification and identification of “cleavage fragments” and “transitional fibers”, mineral particles that are common in crushed Gouverneur talc; these particle types are discussed below.

#### Vermont talc

Talc deposits in Vermont are typical of “black wall” deposits, formed by regional metamorphism and metasomatism of ultramafic rocks, originally composed of dunite or peridotite. These deposits form as zoned alteration “rinds” around ultramafic bodies; the altered zones can be 6.5 km or more long and 460 m wide (Cady and others 1963). The alteration zones are typically comprised of the sequence (Sanford 1982 provides details):

**Table 8**

Compositions determined for the mineral particles shown in Figs. 5 and 6, as compared to the "ideal" compositions of pure talc and anthophyllite. The stoichiometric proportions were calculated from energy dispersive spectroscopy (EDS) analyses

Mineral particle	Normalized cation ratios
Ideal talc	$Mg_3Si_4O_{10}(OH)_2$
Ideal anthophyllite	$(Mg, Fe)_7Si_8O_{22}(OH)_2$ [from $Mg_7Si_8O_{22}(OH)_2$ to approximately $Fe_2Mg_5$ $Si_8O_{22}(OH)_2$ ]
Fibers in Fig. 5	$(Mg_{2.8}, Al_{0.1}, Ca_{0.1}, K_{0.1})Si_{4.2}[O_{10}(OH)_2]^*$
Platy talc, Fig. 6	$(Mg_{2.4}, Ca_{0.1})Si_{4.3}[O_{10}(OH)_2]^*$
Talc spindle, Fig. 6	$(Mg_{2.6}, Ca_{0.1})Si_{4.1}[O_{10}(OH)_2]^*$
Anthophyllite bundle, Fig. 6	$(Mg_{6.8}, Ca_{0.1})Si_{8.1}[O_{22}(OH)_2]^*$
Anthophyllite tuft, Fig. 6	$(Mg_{6.8}, Al_{0.1}, Ca_{0.1})Si_{8.0}[O_{22}(OH)_2]^*$

\*Cation ratios were calculated by stoichiometry on the basis of 11 oxygen atoms for talc and 23 oxygen atoms for anthophyllite. (OH) was assumed to be 2 for both phases

1. ultramafic rocks, grading to
2. a talc-carbonate-dominant zone, grading to
3. a nearly mono-mineralogical talc zone (often of high purity) several centimeters to meters thick, grading to
4. a calcic amphibole-chlorite-rich zone, grading to
5. a chlorite-rich zone, grading to
6. a transitional mixed zone of altered mafic country rock, grading to
7. the mafic country rock.

Black-wall talc deposits are associated spatially with serpentinite masses that in some areas host well-developed chrysotile asbestos (Bain 1942; Cady and others 1963). The alteration zone locally contains actinolite, tremolite, anthophyllite, and (or) cummingtonite, as described by Cady and others (1963). Zodac (1940, p. 370) described "radiating masses of fibrous actinolite, which often have to be handled carefully as the needle-like crystals may penetrate fingers, are common on the dumps" in a talc quarry near Chester, Vermont. This same deposit yielded three biopyriboles newly recognized and named in the 1970s—jimthompsonite, clinojimthompsonite, and chesterite (Veblen and Burnham 1978). These fibrous amphiboles represent intermediate products of incomplete reactions during the conversion of anthophyllite and cummingtonite to talc (Veblen and Burnham 1978).

### Soapstone Ridge, Georgia

As implied by its name, Soapstone Ridge about 13 km south-southeast of Atlanta, Georgia, contains outcrops of impure talc. The deposits formed by regional metamorphism of a large ultramafic body. Analyses of the talcose rock by the U.S. Bureau of Mines (Blake 1982) indicated: (1) mainly prismatic to acicular anthophyllite and cummingtonite, and (2) minor amounts of asbestiform varieties of anthophyllite, cummingtonite, and tremolite in veinlets and fracture fillings.

### Dadeville, east-central Alabama

Regional metamorphism and metasomatism of mafic and ultramafic rocks near Dadeville in eastern-central Alabama provide another example of talc-amphibole associations. This elongate, northeast-trending belt of alteration contains discontinuous pods, seams, and lenses of talc (soapstone), talcose-anthophyllite, talcose-pyroxenite, anthophyllite asbestos, and asbestiform tremolite and actinolite in and along the margins of mafic and ultramafic rocks (Neathery and others 1967; Neathery 1968). Anthophyllite asbestos occurs in veins adjacent to talc rock and fills thin (<2.5 cm thick) veinlets that cut the talc bodies. Selective mining of the Dadeville area talc, while also excluding anthophyllite asbestos, may be impossible or at least impractical. In fact, in regard to the Dadeville area deposits, Neathery (1968, p. 2) noted: "Considerable tonnages of anthophyllite asbestos could conceivably be derived as a primary product or as a secondary product from talc mining".

### Llano uplift, central Texas

Impure talc deposits (soapstone) occur in a regionally metamorphosed terrane of the Llano uplift of central Texas. At least ten large talc bodies have been identified (Barnes 1943); one small mine in the past produced soapstone used mostly for fireplace and hearth linings. Some of the talc bodies replace calcareous tremolite schists, and thus the talcose rock contains considerable amounts of tremolite, which can exceed the talc component. These tremolite-talc bodies occur in a sequence of talc-chlorite schists, chlorite-epidote schists, amphibolite, hornblende schist, serpentinite masses, gneiss, and sometimes vermiculite deposits (Barnes 1943). The tremolite crystals "vary considerably in shape, some being short and blocky and others being in long thin needles" (Barnes 1943, p. 72). Pockets of tremolite asbestos in schist are mentioned, and serpentinite masses sometimes contain pods of chrysotile asbestos (Barnes 1943). Actinolite is noted in one deposit. Barnes (1943, p. 74) interpreted the formation of these deposits "to be roughly: (1) metamorphism of impure dolomites and limestones into tremolite schist and (2) alteration of the tremolite in part at least to talc". Other talc deposits in the region are anthophyllite-rich and lack tremolite; these talcs also replace schist. The talc-anthophyllite bodies are not so closely spatially associated with serpentine (Barnes 1943).

## Complications in evaluating asbestos content

Lending complexity to the determination of the asbestos content in some talc deposits is the presence of amphibole "cleavage fragments" and "transitional fibers". Transitional (dual-phase: talc/amphibole) fibers and cleavage fragments are found as constituents, and sometimes as abundant constituents, of talc ores formed by regional metamorphism. In particular, crushed talc ores extracted



from the deposits of the Gouverneur district of upstate New York contain both amphibole cleavage fragments and transitional fibers (Beard and others 2001). Differing interpretation of these particles has caused considerable disagreement over the “asbestos” content of these talc deposits for more than three decades (Goodwin 1974). “Transitional fibers,” sometimes termed “intermediate fibers,” are composed of fibrous talc and amphibole, in various proportions. They include mineral fibers caught in the act of transformation, such as the incomplete replacement of anthophyllite by talc. X-ray diffraction, optical, and chemical analyses of transitional fibers in many cases either reveal characteristics that range between the ideal values for talc and amphibole or show both the values of talc and amphibole. These transitional fibers may have formed by partial, pseudomorphic replacement of fibrous amphibole by talc and (or) the microscopic intergrowth of amphibole with talc (Virta 1985). For example, in the tremolite-anthophyllite-rich, fibrous talc deposits of the Gouverneur district, Engel (1962) determined that acicular tremolite was the primary metamorphic mineral of the talc ore assemblage, which was replaced locally by pseudomorphous anthophyllite; both tremolite and anthophyllite were subsequently replaced by fibrous talc and serpentine. Where abundant in a talc-amphibole deposit, transitional fibers, such as the example shown in Fig. 6, represent a real challenge to (1) an analyst attempting to quantify the asbestos content of the material, and (2) a toxicologist evaluating the risk potential of the material.

Complexity is added to the analyst’s job because, when crushed, amphiboles readily fracture along cleavage planes often forming acicular particles referred to as cleavage fragments. Analytical studies have shown that cleavage fragments of amphiboles display particle populations with distinctive dimensions (shorter particles of lower aspect ratio), which can be distinguished from the longer, thinner, asbestiform particles (Campbell and others 1979; Zoltai 1979; Dorling and Zusman 1987; Skinner and others 1988; Wylie 1988, 2000). The dilemma of distinguishing cleavage fragments from asbestiform fibers is discussed by Wylie (1988, 2000).

## Discussion

A review of published descriptions of about 360 talc deposits (mines, prospects, and occurrences) in the U.S. reveals that a consistent relationship occurs between the primary talc-forming geologic environment and the amphibole content of the talc deposit. That is, talc deposits formed by hydrothermal processes—meteoric or basin brine fluids heated by buried magma bodies—consistently lack amphiboles as accessory minerals. In contrast, talc ores that formed by contact or regional metamorphism are consistently intermixed with amphiboles, sometimes of the asbestiform variety. These consistent associations were confirmed by a limited amount of field and laboratory studies of commercial talc deposits.

Examples of major talc-producing districts formed by hydrothermal processes include those in southwestern Montana (current production; Van Gosen and others 1998), the Allamoore district of west Texas (current production; Bourbon 1982; Kyle and Clark 1990), and the Talc City district, Inyo County, southern California (World War I and II-era mining; Page 1951). Regardless of the source of the hydrothermal fluids (meteoric, basin brine, or perhaps magmatic) or their heat source (buried or distant intrusions), hydrothermal talc deposits are apparently amphibole-deficient bodies. U.S. talc deposits described as hydrothermal deposits occur in: Alabama (2 deposits; Blount and Vassiliou 1980; Blount and Helbig 1987); California (31 deposits; Page 1951); Montana (64 deposits; Berg 1979), New Mexico (2 deposits; Kottlowski 1965; Fitzsimmons and Kelly 1980); Nevada (27 deposits; Papke 1975a); Texas (45 deposits; Bourbon 1982); and Washington (1 deposit; McHugh 1985). Descriptions of these hydrothermal talc deposits note only occasional amphibole minerals found in trace amounts, typically as rare components of the dolostone country rock. This study sampled hydrothermal talc of the Talc City district, California, and Yellowstone mine, Montana, and found no amphibole minerals in the ore material. Several published fluid inclusion studies indicate that the hot fluids responsible for “hydrothermal talc” deposits were typically saline ( $\text{Na}^{1+}$  and  $\text{Ca}^{2+}$  enriched), and low in  $\text{CO}_2$ , and had temperatures of less than approximately 400 °C.

Talc formed in geologic settings of contact metamorphism is known in a number of instances to be intergrown with amphibole, some of which is asbestiform. Examples include 55 talc-tremolite deposits of the Death Valley region, southern California, which were developed as mines and prospects during the 20th century. This study sampled ore material from ten of these deposits (Table 4). As described earlier, talc ores from the Death Valley deposits were consistently found to contain asbestiform fibers and fiber bundles of amphiboles (likely tremolite, winchite, and richterite), mixed with platy talc. These talc-amphibole-rich rocks massively replaced cherty dolostones immediately against their contact with intruding gabbroic sills. The Death Valley replacement deposits are essentially a friable rock consisting of mostly talc and tremolite, with either mineral predominant, depending on the site; accessory minerals include calcite, dolomite, quartz, phlogopite, magnesiohornblende, sepiolite, clinocllore, kaolinite, muscovite, and saponite. Talc of mainly platy habit is intergrown and disseminated with amphiboles of prismatic to asbestiform habits in these ore bodies.

More examples of talc deposits formed by contact metamorphism occur in western North Carolina, where they are associated with the Day Book dunite (Murdock and Hunter 1946). Serpentinite formed in contact zones where granitic bodies intruded the dunite mass; these serpentine-rich contact aureoles contain intervals enriched in talc and anthophyllite-asbestos (Kulp and Brobst 1954). Intervals within the alteration contact zones, from several centimeters to a meter thick, are described as “talc-rich” zones and “anthophyllite asbestos” zones, but these descriptions are generalized and not intended to imply asbestos-free

and asbestos-bearing zones that are distinct. The impure talc zones (soapstone) may contain amphiboles, including asbestiform amphiboles, and thus deserve petrologic examination.

Although the talc deposits formed in quite different geologic settings—the Death Valley talcs replaced dolomite and the North Carolina talcs replaced altered dunite—the products of contact metamorphism included amphibole asbestos. Thus, talc deposits formed by contact metamorphism must be regarded as potential sites for amphibole asbestos.

Categorization of talc deposits formed by regional metamorphism appears to be less straightforward than for hydrothermal and contact metamorphic deposits.

Amphiboles are ubiquitous in talc deposits formed by regional metamorphism, most commonly as anthophyllite and tremolite-actinolite series minerals. The crystal habits of the amphiboles are quite variable in these metamorphic talc deposits, commonly ranging from blocky to prismatic to acicular to asbestiform within a single outcrop.

The distribution of amphiboles within talc deposits formed by regional metamorphism is also variable between districts. For example, the deposits mined in the Gouverneur mining district in north-central New York State contain an abundance of fibrous talc-amphibole intergrowths that replaced dolomitic marbles (Engel 1962; Ross and others 1968; Virta 1985; Greenwood 1998). The intimate intergrowth of talc and amphibole in the Gouverneur deposits likely formed during retrograde metamorphism in which talc replaced pre-existing amphibole. As a result, talc and amphibole are intermixed in the Gouverneur deposits. In contrast, the “black wall” deposits in Vermont, which formed by regional metamorphism and metasomatism of ultramafic rocks, are zoned deposits in which some of the talc intervals, up to a few meters thick, are often of high purity (Cady and others 1963). The adjacent rock sequence can contain actinolite, tremolite, anthophyllite, and (or) cummingtonite, locally occurring in fibrous habits. These examples from New York and Vermont, as well as talc districts in Georgia, Alabama, and Texas (described earlier), demonstrate that talc deposits formed by regional metamorphism are consistently associated with amphiboles, sometimes with asbestiform habits, but their amphibole distribution is variable and deserves site-specific geologic examination and sampling. Determining the quantity, or actual presence, of asbestiform amphiboles within talc deposits formed by regional metamorphism often produces a variety of estimates by different analysts and by different optical techniques (Wylie 2000). Additionally, amphibole cleavage fragments and transitional fibers lend more complexity to the estimation of asbestos content in crushed examples of these talc ores (discussed above). Variability of amphibole particle size and habit within deposits formed by regional metamorphism has often placed this particular type of talc deposit at the middle of controversies regarding the safety of talc materials. Thus, whereas analysis of amphibole content and character within any particular talcose material is always best done on a site-by-site basis, site-specific analyses are especially advised where the mineral deposit

is thought to have formed by regional metamorphic or contact metamorphic processes. The recommendation of techniques for the analyses of amphiboles in talc ores, particularly those formed by regional metamorphism, is beyond the focus and intent of this study; the reader is instead referred to Beard and Rooks (2000).

## Conclusions and recommendations

This study revealed that the primary talc-forming conditions—due to hydrothermal processes, contact metamorphism, or regional metamorphism—had a direct influence on the ultimate amphibole content of the talc body. Talc deposits formed by hydrothermal processes—meteoric, basinal brine, or possibly magmatic fluids heated by magma bodies at depth—consistently show negligible amounts or a complete absence of amphibole. Talc deposits that formed in environments of contact metamorphism show a strong tendency to contain asbestiform amphibole within the talc ore. Talc deposits formed by regional metamorphism consistently contain amphiboles, but the amphibole particle habits and sizes are quite variable, requiring careful site-specific study. Given the re-focus of attention upon the potential hazards of amphibole asbestos in some industrial mineral deposits, these talc-amphibole relationships may be useful as a first-level screening tool in prioritizing sites for the monitoring or remediation of active and abandoned talc mines.

A review of the fluid-inclusion literature revealed that talc deposits associated with ore-forming fluids cooler than  $\sim 400$  °C consistently lack amphiboles as accessory minerals. In contrast, talc deposits that formed from higher temperature fluids are typically mingled with amphiboles (Sanford 1982; Walther 1983; Park and others 1997), including amphiboles that in some instances are locally asbestiform. Thus, the fluid temperature(s) of the system may have played an important role in determining the presence or absence of amphibole, and thus amphibole asbestos, within the talc deposit. The geologic environment must play an important role in determining the chemistry and temperature of the talc-forming fluids:

1. hydrothermal talc deposits formed via relatively cool fluids ( $<400$  °C) heated by distant sources, such as buried plutons,
2. contact-metamorphic talc deposits formed against igneous intrusions in localized areas of high temperature conditions, and
3. regional-metamorphic deposits formed in relatively high temperature-pressure environments.

Localized conditions within these talc-forming environments ultimately controlled the deposition or non-deposition of amphiboles and, by association, amphibole asbestos.

The talc-forming systems are complex and fluid temperature alone may not adequately explain talc±amphibole crystallization. Several other parameters should also be considered in system modeling, such as:

1. pressure,
2. the activities of Si, Ca, Mg, and perhaps other chemical components (CO<sub>2</sub>) in the system,
3. fluid-flow mechanisms (diffusion, infiltration),
4. the chemical composition of the host rocks,
5. water-rock ratios, and
6. reaction rates.

Reaction-path modeling of these parameters was beyond the current scope of this study. However, mineralogical, chemical, and fluid-inclusion studies are underway at the USGS to better recognize and explain the talc- and asbestos-forming geologic settings, thereby providing insights towards asbestos geology that can be applied to decisions required by land managers, and health and safety administrators.

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