An overview of the mining history, geology, mineralogy, and amphibole-asbestos health effects of the Rainy Creek igneous complex, Libby, Montana, U.S.A.: A case study in teaching environmental mineralogy

(modified from Bandli, B. R. (2002) Characterization of amphibole and amphibole-asbestos from the former vermiculite mine at Libby, Montana, U.S.A., M.S. Thesis, University of Idaho, Moscow, Idaho, U.S.A.)

ABSTRACT

The Rainy Creek igneous complex is an alkaline-ultramafic igneous intrusion in Lincoln County, Montana and is locally known as Vermiculite Mountain. Hydrothermal alteration and extensive weathering of the ultramafic units resulted in the formation of a rich deposit of vermiculite that was mined for 67 years and used in numerous consumer products in its expanded form sold under the trade name Zonolite. Later intrusions of alkaline magmas caused hydrothermal alteration of the pyroxenes resulting in formation of amphiboles. Approximately one-half of the amphiboles occur in the asbestiform habit and are associated with pulmonary diseases in former miners and mill workers. Identification of these amphibole minerals received little attention, but recent work shows the mineral species, mainly winchite and richterite, are not any of the asbestos species currently regulated by government agencies.

Articles in the popular press published late in 1999 stated there were increased risks of asbestos-related diseases among the former vermiculite miners, and a recent study by the Agency for Toxic Substances and Disease Registry has shown that residents of Libby also appear to have developed asbestos-related pulmonary diseases at a higher rate than the general public. Since November of 1999, the United States Environmental Protection Agency has been involved in the cleanup of asbestos contaminated sites in and around Libby associated with the mining and processing of vermiculite. On a much larger scale, are issues surrounding the possible remediation of 10-20 million homes in the U.S.A. that contain Zonolite insulation at an estimated cost exceeding $10,000,000,000.

INTRODUCTION

This paper is an overview of the past 90 years of scientific research directed at multiple aspects of the former vermiculite mine near Libby, Montana. During its operation it was the largest producer of vermiculite in the world. Unfortunately the ore shipped from the mine contained a small percentage of amphibole-asbestos. The many issues surrounding Libby are introduced with the hope of providing background information to use Libby as a case study in teaching environmental mineralogy. Gunter (1994, 1999) presented similar articles on the environmental concerns of asbestos and quartz, and Lang (1998) suggested such issues provide our students case studies to examine the societal significance of mineralogy. Libby, and the former mine site, were basically unheard of before November 1999; however, since then issues surrounding Libby have garnering national press, are causing modifications in asbestos regulations, may result in billions of dollars of remediation costs, and are causing fear among millions of U.S. homeowners.

The first examination of the Rainy Creek igneous complex (RCC) was during gold explorations in the late 19th century. Pardee and Larsen (1929) began work in the area exploring the quartz veins in 1911. It was these early explorations, particularly by E.N. Alley, who observed exfoliation of vermiculite in the roof of exploration audits, which led to the discovery and large-scale mining of the vermiculite deposits in the area of Rainy Creek (Pardee and Larsen, 1929). (See Table 1 for timeline of important events.) During the 1920's, the Zonolite Company developed the deposit, and uses for exfoliated (expanded) vermiculite led to increased production. W.R. Grace Corporation purchased the mine from the Zonolite Company in 1963 and continued producing expanded vermiculite for its products such as Zonolite insulation and Monokote fireproofing, bulking agents, absorbents, and soil amendments. They increased production, and eventually the mine at Libby was the largest source of vermiculite worldwide. Along with the mine at Libby (Figures 1 A-C), W.R. Grace also operated an export facility and local expansion facilities (until 1990). The mine at Libby ceased operation in 1990. The vermiculite ore is contaminated with varying amounts of amphibole-asbestos (Figures 1 D-F), which formed as a result of hydrothermal alteration of pyroxene minerals. MEG collected geological and mineralogical samples from the former W.R. Grace vermiculite mine in October of 1999. Photographs in Figure 1 were also taken at that time. The crystal chemistry and morphology of these samples are discussed in Gunter et al. (2003). Since the involvement of the EPA in the asbestos cleanup, access to the former mine site has become extremely difficult.

Several epidemiological studies have documented the toxicity of the amphibole-asbestos minerals in the RCC. However, the species of amphibole has been misidentified as tremolite-asbestos in these studies. Recent work by Wylie and Verkouteren (2000) and Gunter et al. (2003) shows that the amphibole minerals are actually winchite and richterite. The asbestos minerals in the RCC appear to have significant effects on humans. The incidence of asbestosis, mesothelioma, and lung cancer is high in former mine workers, particularly those employed in the early unregulated workplace. The Agency for Toxic Substances and Disease Registry (ATSDR 2001) presented data that showed a significant number of individuals who lived in Libby and did not work in the mining or processing of vermiculite, show symptoms of diseases related to asbestos exposure. Currently, the United States Environmental Protections Agency (EPA) is proposing to list mining and milling operation sites in Libby as a Superfund site.

MINING HISTORY

Mining and processing of vermiculite from the RCC continued uninterrupted from 1923 to 1990 (Table 1). E.N. Alley was the first individual to exploit the RCC vermiculite deposit in 1923. The incorporation of the Universal Zonolite Insulation Company and the Vermiculite and Asbestos Company were the first commercial ventures of the vermiculite deposits at Libby. In 1948, these two companies merged to become the Zonolite Company.

The processes involved in mining and milling the vermiculite did not change much over the lifespan of the mine (Table 1). Initially, vermiculite ore was removed from underground workings, but eventually surface mining methods (Figures 1 B & C) were employed. The ore was generally very weathered and could be removed without blasting, but blasting was occasionally necessary. The mine was a large open pit that eventually covered several hundred acres (Figures 1 A & B and Figure 2). Ore was hauled to a transfer point on the west end of the mine (USEPA, 2001), where it was passed through a grizzly to remove the coarse fractions, and the remaining ore was transferred by conveyor to the concentrating/loading facility on the Kootenai River at the mouth of Rainy Creek (Figure 3) (Boettcher, 1963). In the mill, the vermiculite was concentrated through a dry beneficiation process until 1954, when a wet beneficiation process was developed. Both processing methods were used until 1974 when the dry process was discontinued. Next, the concentrate was screened into 5 grades based on particle size. A portion of the vermiculite concentrate was sent to an exfoliating and export plant in Libby. However, the majority of the vermiculite concentrate was transferred across the Kootenai River by conveyor for shipment by rail to expansion facilities across the United States (USEPA, 2001).

At the expanding facilities the vermiculite was heated in kilns to approximately 1100˚ C for a few seconds (Bassett, 1959). This rapid heating caused the water in the vermiculite structure to vaporize, forcing the layers apart and creating the useable product (Figure 4). W.R. Grace marketed the majority of the expanded vermiculite originating from its Libby mine as Zonolite insulation. The mining and processing operations at Libby were very dusty by nature, and owners of the mine and various regulatory agencies worked to reduce the levels of dust exposure. Regulations regarding acceptable limits of the amount of airborne asbestos fiber workers can be exposed to are listed in Table 2, and these limits decreased over time.

GEOLOGY

The RCC is an alkaline-ultramafic igneous complex in Lincoln County, Montana seven miles northeast of Libby and is locally known as Vermiculite Mountain (Figure 5). The RCC lies in the basin of Rainy Creek and is much less resistant to erosion than the surrounding Belt series metamorphic rocks. The contact between the ultramafic and metamorphic units is topographically expressed in a significant increase in slope in the metamorphic units. There is also a significant decrease in the density of coniferous vegetation growing in soils over the ultramafic units (Boettcher, 1963). The rocks of the complex, where not exposed by mining, are covered by till (Larsen and Pardee, 1929). The geology of the RCC has been studied by several individuals: Goranson (1927), Pardee and Larsen (1929), Larsen and Pardee (1929), Kriegel (1940), Bassett (1959), Boettcher (1963, 1966a, 1966b, 1967), and is currently being studied by the United States Geological Survey (Meeker et al., 2003). Boettcher provides the most detailed and most recently published geologic and mineralogical information on the RCC.

The rocks of this igneous complex formed by intrusion into the Precambrian Belt series (Wallace Formation) (Figure 5). The magma intruded into the axis of a slightly southeasterly plunging syncline (Figure 5). The rocks of the RCC consist of biotitite, biotite pyroxenite, magnetite pyroxenite, syenite, trachyte, phonolite, and granite (Boettcher, 1967). Workers prior to Boettcher (1967) collectively described the biotite pyroxenite and magnetite pyroxenite as pyroxenite. The main body of the complex is a stock composed predominantly of biotite pyroxenite, magnetite pyroxenite, and biotitite. A large, irregularly shaped body of altered nepheline syenite crosscuts the pyroxenites (Figure 5). All of these units are crosscut by trachyte and phonolite dikes, which are, in turn, cut by granitic dikes (Boettcher, 1963).

Biotitite: The central and topographically highest unit of the complex is a coarse-grained biotitite that comprises approximately 5% of the intrusion. The biotitite is composed almost entirely of anhedral books of biotite that are generally larger than 10 cm and show no preferred orientation (Boettcher, 1966a). The biotitite was thought by Boettcher to have formed near the roof of the magma chamber in the presence of higher concentrations of alkali metals, metal sulfides, and volatiles relative to the surrounding pyroxenites. Larsen and Pardee (1929) mentioned a "biotite rock," but it does not appear to be the biotitite unit described by Boettcher (1967). The Larsen and Pardee (1929) "biotite rock" was described as being almost entirely altered to vermiculite, whereas the biotitite described by Boettcher is composed of unaltered biotite with only small amounts of vermiculite.

Feldspars occur as wedges between books of biotite and make up less than 10% of the rock. Small amounts (<2%) of pyrite and calcite occur as secondary alteration products. Calcite is evenly distributed throughout the biotitite as a secondary alteration product of the biotite (Boettcher, 1966a). The contact between the biotitite and the biotite pyroxenite is gradational over 3 m. The contact zone is also expressed in a compositional change, where feldspar content decreases to zero while diopside and vermiculite content increase significantly (Boettcher, 1967).

Biotite pyroxenite: The biotite pyroxenite completely surrounds and has a gradational contact with the inner biotitite (Figure 5). The biotite pyroxenite makes up approximately 20% of the intrusion (Boettcher, 1967). In hand sample, it is dark green, and although friable (Fig 1D), most of the diopside appears unaltered. The biotite pyroxenite ranges in size from <1 mm to >10 cm, and is composed of variable amounts of clinopyroxene (diopside), biotite, vermiculite, and hydrobiotite. This unit was the source of all the mineable vermiculite, and vermiculite content varies significantly, but on average is 25 wt.% (Boettcher, 1966a). Unaltered biotite can be found locally within the biotite pyroxenite. Bassett (1959) observed areas where pyroxene crystals were horizontally oriented but were crosscut by veins of fine-grained pyroxenite where the pyroxenes were oriented vertically. This would indicate some sort of vertical flow of the magma prior to complete crystallization, according to Bassett (1959). Apparently, this feature does not occur over large areas of pyroxene-bearing units and Boettcher (1966a) contradicts Bassett (1959) by noting that most of the pyroxene crystals do not show this preferred orientation. The largest grains of diopside occur nearest to the contact with the biotitite. Fluorapatite is the most common accessory mineral and occurs as interstitial euhedral crystals and as small crystals within the diopside crystals (Boettcher, 1966a). The biotite pyroxenite and biotitite appear to be comagmatic (Boettcher, 1967). Several dikes of magnetite pyroxenite, have intruded into the biotite pyroxenite indicating a discontinuity in the intrusion of the ultramafic portion of the complex.

Magnetite pyroxenite: The magnetite pyroxenite has a uniform grain size (0.7-3 mm) and is composed of diopside, magnetite, and apatite with andradite, titanite, and biotite or vermiculite as accessory minerals. It constitutes approximately 40% of the intrusion (Boettcher, 1966a). The orientation of the magnetite pyroxenite relative to the two inner units is like that of a ring dike (Figure 5). The magnetite pyroxenite completely surrounds the inner units and the contact dips slightly outward from the center of the complex in all directions (Boettcher, 1966a). Diopside and apatite crystals are aligned and dip out from the center at varying angles. The magnetite pyroxenite also forms numerous small dikes that crosscut the biotite pyroxenite. The emplacement of the magnetite pyroxenite is thought to have occurred as an intrusion into a zone of weakness that formed between the Wallace Formation and the biotite pyroxenite (Boettcher 1967). The diopside in both of the pyroxenites is aluminum-deficient (Boettcher, 1967) as a result of the early fractionation of the biotitite.

The remainder of the complex (approximately 35%) is composed of various alkaline rocks: syenite, nepheline syenite, trachyte, phonolite, alkaline pegmatite, and alkaline granites. The largest alkaline unit is an irregularly shaped body of variably altered syenite located in the southwest portion of the complex (Figure 5) and transects the earlier ultramafic units. This syenite has been altered and is observed in the replacement of nepheline by muscovite (Boettcher, 1966a). Syenite also occurs as dikes of varying width and is probably genetically related to the alkaline pegmatite dikes (Boettcher, 1966a). These dikes crosscut all of the ultramafic units. The smaller syenite dikes exhibit some compositional and textural variability that could be attributed to multiple intrusions of syenite magma (Larsen and Pardee, 1929). Intrusion of these dikes into the pyroxenite units caused significant wall rock alteration, resulting in the amphibolitization of pyroxene minerals. However, where these dikes occur in the biotitite, little alteration of the biotite is observed. Dikes of trachyte, phonolite, and alkaline granite crosscut both these syenite and alkaline pegmatite dikes. The trachyte and phonolite dikes are interesting in that no wall rock alteration resulted from their intrusion. This feature suggested to Boettcher that theses dikes penetrated near to the surface.

MINERALOGY

Two major processes have significantly influenced the mineralogy of the RCC: magmatic differentiation and hydrothermal alteration. The biotitite and the biotite pyroxenite are believed to have been the first units to crystallize from the original ultramafic magma (Boettcher, 1967). The early crystallization of large amounts of biotite preferentially differentiated aluminum from the melt. This early separation of biotite from the melt was facilitated by a high pH_2O (Boettcher, 1967). Boettcher concluded that the biotitite, biotite pyroxenite, and magnetite pyroxenite are comagmatic. Later, syenite, trachyte, phonolite, and pegmatites intruded the previous units from a much more felsic magma and resulted in the alteration of diopside to amphiboles and biotite to vermiculite and hydrobiotite (Boettcher, 1967). The RCC still contains a large reserve of mineable vermiculite; however, the health effects associated with the amphibole-asbestos minerals in the pyroxenite units makes mining and milling of the vermiculite from this deposit a health hazard.

Biotite, vermiculite, and hydrobiotite: The biotitite unit is almost entirely composed of biotite, whereas biotite comprises roughly 40% of the unaltered biotite pyroxenite and slightly less of the magnetite pyroxenite. Weathering of biotite in the biotite pyroxenite resulted in the formation of the vermiculite. Bassett (1959) and Boettcher (1966b) explored the chemical conditions necessary for the conversion of biotite to vermiculite. The hydrobiotite and amphibole are the product of higher temperature hydrothermal processes (Boettcher, 1966b).

The vermiculite of the RCC was shown by Boettcher (1966b) to have an upper stability limit of 350 ºC. The chemistry of vermiculite indicates it was the result of leaching of biotite by groundwater. A lower content of alkali metals and higher amount of Fe^{3+} than that of biotite indicates a low-temperature leaching process altered the biotite to vermiculite. The hydrobiotite was shown in the same study to have an upper stability limit of as high as 480 ºC. The hydrobiotite has a 1:1 stacking sequence of vermiculite and biotite that is not inherited from the biotite. This, along with the lack of a direct chemical relationship between hydrobiotite and biotite, indicates a much higher temperature hydrothermal alteration process. Bassett (1959) mentioned that miners used subtle color differences as an *ad hoc* method to distinguish areas in the mine richer in vermiculite than biotite or hydrobiotite; the biotite is black and durable, while the vermiculite is golden brown and friable.

Pyroxenes: The pyroxenes in the pyroxenite units are predominantly light green, non-pleochroic diopside (Boettcher, 1966a). Pyroxene accounts for over half of the minerals in the pyroxenite units. In hand sample, the diopside has perfect (100) parting and is emerald green in the biotite pyroxenite and darker green in the magnetite pyroxenite (Boettcher 1967a). The iron content of the diopside is elevated in later crystallizing units and especially when diopside is found in association with magnetite. The RCC also contains aegirine that has been examined by Goranson (1927) and Pardee and Larsen (1929). The aegirine is of interest because of its increased vanadium content. It occurs as black acicular crystals up to 2.5 cm in length that project from the walls of veins or as radiating nodules embedded in other minerals of the pegmatites occurring within the pyroxenites and biotitite.

Amphiboles: Amphibolitization of the pyroxenes in the biotite pyroxenite produced nearly all of the amphibole in these rocks. Identifying the various amphibole species requires detailed chemical analysis (Leake et al., 1997). Until recently, there has been some confusion as to the classification of the asbestos minerals at Libby. Pardee and Larsen (1929) named the amphibole-asbestos minerals tremolite but stated there were "considerable" amounts of Na and Fe in their samples. The EPA and its contractors misidentified these minerals as tremolite (USEPA, 2000). The TEM-EDS data presented in the EPA study (USEPA, 2000) of vermiculite garden products shows that the samples from Libby vermiculite contain significant amounts of Na and K. This would mean these amphibole minerals could not possibly be tremolite. However, the incorrect name tremolite or actinolite persists in EPA literature and in the popular press. The amphiboles in the RCC have been called tremolite-actinolite (Larsen and Pardee, 1929), richterite (Larsen 1942), tremolite-actinolite (Bassett 1959), tremolite (Boettcher, 1963), richterite (soda tremolite) (Deer et al., 1963), and winchite (Wylie and Verkouteren, 2000, Gunter et al., 2003). With the exception of Larsen (1942), Wylie and Verkouteren (2000), and Gunter et al. (2003), no previous worker had performed a chemical analysis of the amphibole mineral to correctly classify it. Meeker et al. (20003) performed chemical analysis of 30 samples they collected from various locations at the former mine site, and found approximately 70% of the amphiboles to be winchite, 20% richterite, 8% tremolite, and 2% magnesioriebeckite.

Since the current OSHA and EPA regulations do not regulate all amphibole-asbestos minerals, it is crucial to understand the precise definition of the mineralogy of any asbestos containing material. The health effects associated with exposure to the amphibole-asbestos from this location are well documented (discussed below). This would suggest that current regulations regarding amphibole asbestos should be revised to include all amphibole-asbestos minerals, or at least winchite and richterite. Regardless of the mineral species or regulations, it is clear that the amphibole-asbestos mineral at Libby should be regulated in order to prevent unnecessary risk to public health.

HEALTH EFECTS

General health effects of inhaled mineral dust: It is generally understood that inhalation of mineral dusts will cause specific lung diseases to develop. There are numerous reviews on the health effects of inhaled mineral dusts. For instance, Reviews in Mineralogy Vol. 28 (Guthrie and Mossman, 1993) is a comprehensive presentation of mineralogical and medical topics related to how inhaled minerals affect human health, and the Canadian Mineralogist Special Publication #5 (Nolan et al., 2001) outlines the health effects associated with environmental exposure to chrysotile asbestos, with some discussion of amphibole-asbestos. Three diseases are associated with occupational exposure to asbestos: asbestosis, mesothelioma, and lung cancer.

Asbestosis is a type of pneumoconiosis that results from inhalation of large quantities of asbestos. Pneumoconiosis is a general term used to describe a disease associated with inhalation of large amounts of a specific type of dust into the lungs, and is a fibrotic lung disease where the alveoli are destroyed by the minerals. This hinders the lung's ability to exchange oxygen and carbon dioxide; as a result of decreased lung function, the heart is forced to pump faster, and a person with asbestosis usually dies from heart failure. Silicosis and anthracosis (black lung) are two types of pneumoconiosis associated with inhalation of quartz dust and coal dust, respectively (Gunter, 1999). In 1999, 1259 people in the United States died as a result of asbestosis (Centers for Disease Control (CDC), 2001).

Mesothelioma is a disease of the lining of the lung, the pleura, usually in the form of plaques. Plaques are not necessarily harmful; however, it is unclear if there is a connection between pleural plaques and malignant mesothelioma, which is usually fatal. It is not known why inhaled asbestos minerals cause reactions to occur in the pleura. Mesothelioma has a very long latency period, so it is difficult to diagnose and treat in early stages. This long latency period complicates the process of determining how much asbestos an individual was exposed to prior to developing the disease. In 1999, 2502 people in the United States died as a result of mesothelioma (CDC, 2001).

Lung cancer is the third major disease associated with asbestos exposure. In 1998, 154,561 people died as a result of lung cancer in the United States (American Lung Association (ALA), 2001). However, most lung cancer cases are associated with cigarette smoking. Therefore, it becomes difficult to separate lung cancers that may not have been caused by asbestos from those caused by other carcinogens.

The amount of a certain mineral a person inhales is an important factor to consider. A fundamental concept of the study of mineral-induced lung diseases is that the dose makes the poison (Gunter, 1994). Mesothelioma and lung cancer may develop after inhalation of moderate or small quantities of asbestos dust. The relationship between dose and disease is complicated and has yet to be accurately defined.

It also appears that the type of asbestos an individual inhales is an important factor in determining what lung disease may develop. Epidemiological studies indicate variability in the potential for different asbestos minerals to cause diseases in humans. Amphibole asbestos minerals pose a much greater threat than other asbestos minerals (Kane, 1993). Tremolite has been described as the most dangerous of the amphibole-asbestos minerals (Case, 1991), though this was, ironically, based on the definitive epidemiological studies of workers exposed to "tremolite-asbestos" from the Libby vermiculite mine.

Regardless of the species of amphibole-asbestos, it appears that amphibole-asbestos minerals pose a greater risk than chrysotile asbestos (Gunter, 1994). This is for a variety of reasons, including the fact that amphiboles are insoluble when exposed to the chemical conditions in the lung. Many case and *in vitro* studies have shown that when dusts containing significant amounts of chrysotile and minor amounts of amphibole-asbestos are inhaled, lung burdens at the time of death contain many more amphibole-asbestos fibers than chrysotile fibers (Davis et al,. 1991). It has also been shown that the carcinogenic potential of amphibole-asbestos is significantly higher than that of other minerals (Weill et al., 1990). It is important to note that amphibole-asbestos has not been extensively mined or used in manufactured products and exposure is usually through background environmental dust or as a contaminant in some other mined or quarried material (Ross, 1981). However, the probability that background environmental exposure to amphibole-asbestos results in asbestos-related lung disease, mesothelioma in particular, is very small (Browne and Wagner, 2001).

The health effects associated with amphibole minerals may also be dependent on the morphology of the inhaled particles. Asbestos fibers appear to pose a greater risk than cleavage fragments. There also appears to be a correlation between increased potential to cause disease and increased aspect ratio. The result of this is that amphibole cleavage fragments (which have a low aspect ratio) have not been shown to cause disease in humans and are therefore not regulated, whereas asbestos fibers (which have a high aspect ratio) are known to cause disease and are regulated (Dorling and Zussman, 1987). It has also been noted that there may be a correlation between particles that exhibit (110) cleavage and those that exhibit (100) twinning and effects on human health (Zoltai 1981), and there may also be a correlation between increased disease potential and other dimensional ratios that have yet to be studied (Davis et al., 1991). Gunter et al. (2003) showed that approximately one half of amphiboles at Libby exhibit asbestiform morphology based on counting of several hundred particles with a polarizing light microscope.

Health effects observed in Libby: Health effects observed in Libby workers are typical of other groups exposed to amphibole-asbestos. It is important to note that no adverse health effects have been observed from exposure to vermiculite alone (Ross et al., 1993). Lockey et al. (1984) examined a group of vermiculite workers who were exposed to "tremolite-asbestos" in the vermiculite ore, and determined that occupational exposure to asbestos-contaminated vermiculite could cause pleural changes. Other epidemiological studies showed substantially increased risks of lung cancer, malignant mesothelioma, and pleural changes (McDonald et al. 1988; Amandus 1987b).

The studies of McDonald et al. (1986a, 1986b, 1988), Amandus and Wheeler (1987), and Amandus et al. (1987a, 1987b) were performed in parallel and studied the health of men who were involved with mining and processing the vermiculite from the RCC. W.R. Grace funded the McDonald et al. (1986a, 1986b, 1988) studies, and the National Institute for Occupational Safety and Health (NIOSH) funded the Amandus and Wheeler (1987) and Amandus et al. (1987a, 1987b) studies. Both studies estimated the amounts of airborne asbestos workers were exposed to and calculated standard mortality ratios (SMR) for various diseases. These studies provide the definitive evidence that the amphibole-asbestos from the RCC is harmful to humans.

McDonald et al. (1986a, 1986b, 1988) showed that there was a significantly higher incidence of lung cancer and nonmalignant respiratory disease in workers of the Libby vermiculite mine. The study examined the exposure levels and health histories of 406 men employed for at least one year before 1963. It was determined that the SMR for lung cancer (SMR = 2.45) and nonmalignant respiratory disease (SMR = 2.55) were significantly higher for this cohort than for the white male population of the United States (McDonald et al., 1986a). The exposure levels were variable and dependent on workstation activity (Table 3) (McDonald et al., 1986b). It was shown that after W.R. Grace acquired the mine, dust levels decreased significantly. It was also shown that for each fiber-year of exposure there was a 1% increase in the probability of a worker developing lung cancer (McDonald et al., 1988).

Amandus and Wheeler (1987) and Amandus et al. (1987a, 1987b) replicated the studies of McDonald et al. (1986a, 1986b, 1988). These studies examined the exposure levels and health histories of 575 men who had been hired before 1970 and were employed at least one year. Exposure estimates (Amandus et al., 1987a) were determined using previous measurements and workstation activities. Amandus et al. (1987a) estimated the exposure rates for workers at the Libby vermiculite operations and determined that from the onset of mining to the mid 1980’s there was a significant decrease in the levels of airborne asbestos (Table 3). These data were used to determine individual cumulative fiber exposure (fiber-year). The estimates show that, in general, exposure was highly variable depending on a worker's workstation activity. SMR for lung cancer (SMR = 2.44) and nonmalignant respiratory diseases (SMR = 2.42) were found to be significantly higher than that of the general white male population in the United States. The increase in the risk of developing lung cancer was determined to be 0.6% for each fiber-year of exposure (Amandus and Wheeler, 1987). These two studies show that the asbestos minerals present in the Libby vermiculite ore posed a significant health risk to workers who were exposed at high levels.

Both McDonald et al. (1986a) and Amandus et al. (1987a) showed that workers employed before 1970 were exposed to significantly higher levels of amphibole-asbestos than those employed later. Table 3 gives estimated amphibole-asbestos dust levels at various workstations during the life of the mine. Dust levels were not measured in all years, so dust levels were assumed to remain constant until the next measurement was made. The data show several significant changes in the amounts of dust the workers at Libby were exposed to. Dust levels were extremely high in the dry mill before W.R. Grace acquired the operation in 1963, and dust levels were reduced by approximately 75% by 1965. With the elimination of the dry mill in 1974, the largest source of airborne amphibole-asbestos fibers was removed, and with the introduction of federal regulations in 1972 (Table 2), the fiber exposure for workers was reduced further. The McDonald et al. (1986a) estimates are consistently lower than those of Amandus et al. (1987a), but both show the consistent trend of decreasing fiber exposure with time.

Preliminary results of a recent Agency for Toxic Substances and Disease Registry study (ATSDR, 2001) of 5590 Libby residents reveal that 18% of the population have pleural abnormalities; 2% had no direct exposure to asbestos, and 5% of those who had no direct exposure (0.1% of the study group) have lung abnormalities consistent with asbestos exposure. This may mean that the asbestos at Libby is hazardous even at very low exposure levels. However, there is very little information about how much asbestos residents of Libby were actually exposed to. The major concern is that environmental exposure to the amphibole-asbestos from Libby is harmful.

SUMMARY

The RCC alkaline-ultramafic igneous intrusion was mined for 67 years for its rich deposit of vermiculite, which has numerous industrial applications. It still contains significant amounts of vermiculite ore. However, the geologic processes that created the vermiculite also created amphibole-asbestos. As pressure from the regulatory agencies and residents of Libby to remove asbestos contamination from the vermiculite mining and milling operations in Libby and elsewhere around the U.S. continues, more information about exactly what species of amphibole minerals will be required. The classification of the amphibole-asbestos in vermiculite products that originated from the Libby mine has been clouded in confusion. For the past two years, the EPA and the media have continued to call these amphibole minerals tremolite when indeed they are not. Correct classification of these harmful minerals will require a change in the regulations to protect human health. Ironically and interestingly, much of the health risks of tremolite have been based on the misconception that the amphibole and amphibole-asbestos found at Libby was tremolite.

Since November of 1999, the EPA has been actively involved in abatement of asbestos contamination resulting from the vermiculite mining and milling operations at Libby. The main focus of the EPA's cleanup effort has been on the export plant at the mouth of Rainy Creek, but several other sites in Libby, including the Libby High School, Burlington Northern and Santa Fe Railway yard, and multiple residential areas are being considered for asbestos cleanup projects. Currently, the EPA is considering placing these areas in Libby on its National Priority List or listing the area as a Superfund site. Tens of millions of dollars have already been spent cleaning up the former export plant and several other locations in Libby where vermiculite was used for various purposes. In order to clean up all asbestos contamination in Libby, it will take between $40 and $60 million over 3 years (Drumheller, 2001). A final decision by the EPA as to how it will deal with asbestos contamination at Libby will be made in the near future. It will also be necessary to decide how to handle the vermiculite insulation that was used in millions of homes across the United States, and to examine the levels of asbestos contamination that occurred at the numerous vermiculite expansion facilities that were operated by Zonolite and W.R. Grace.

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REFERENCES CITED

Amandus, H.E. and Wheeler, R., 1987, The morbidity and mortality of vermiculite miners and millers exposed to tremolite-actinolite: Part II. Mortality: American Journal of Industrial Medicine, v. 11, p. 15-26.

Amandus, H.E., Wheeler, R., Jankovic, J., and Tucker, J., 1987a, The morbidity and mortality of vermiculite miners and millers exposed to tremolite-actinolite: Part I. Exposure estimates: American Journal of Industrial Medicine, v. 11, p. 1-14.

Amandus, H.E., Althouse, R., Morgan, W.K.C., Sargent, E.N., and Jones, R., 1987b, The morbidity and mortality of vermiculite miners and millers exposed to tremolite-actinolite: Part III. Radiographic findings: American Journal of Industrial Medicine, v. 11, p. 27-37.

American Lung Association, 2001, Trends in lung cancer morbidity and mortality, p. 22. American Lung Association, New York.

Agency for Toxic Substances and Disease Registry, 2001, Year 2000 medical testing of individuals potentially exposed to asbestoform minerals associated with vermiculite in Libby, Montana, 30p: U.S. Department of Health and Human Services, Atlanta, Georgia.

Bassett, W.A., 1959, The origin of the vermiculite deposit at Libby, Montana: American Mineralogist, v. 44, p. 282-299.

Boettcher, A.L., 1963, Geology and petrology of the Rainy Creek intrusive near Libby, Montana. M.S. thesis, 70p.: Pennsylvania State University, University Park.

Boettcher, A.L., 1966a, The Rainy Creek igneous complex near Libby, Montana. Ph.D. dissertation, 155p.: Pennsylvania State University, University Park.

Boettcher, A.L., 1966b, Vermiculite, hydrobiotite, and biotite in the Rainy Creek igneous complex near Libby, Montana: Clay Minerals, v. 6, p. 283-296.

Boettcher, A.L., 1967, The Rainy Creek alkaline-utramafic ingeous complex near Libby, Montana. I: Ultramafic rocks and fenite: Journal of Geology, v. 75, p. 526-553.

Browne, K. and Wagner, J.C., 2001, Environmental exposure to amphibole-asbestos and mesothelioma. In Nolan, R.P., Langer, A.M., Ross, M., Wicks, F.J., Martin, R.F., Eds. (2001) The health effects of chrysotile asbestos: contribution of science to risk-management decisions, 304p.: Special Publication #5, Mineralogical Association of Canada, Ottawa.

Case, B.W., 1991, Health effects of tremolite. In P.J. Landrigan, H. Kazemi, The thrid wave of asbestos disease: Exposure to asbestos in place, Annals of the New York Academy of Sciences, v. 643, p. 491-504.

Centers for Disease Control, 2001, Health, United States, 2001, 460 p.: Centers for Disease Control, Atlanta, Georgia.

Davis, J.M.G., Addison, J., McIntosh, C., Miller, B.G., and Niven, K., 1991, Variations in the carcinogenicity of tremolite dust samples of differing morphology. In P.J. Landrigan, H. Kazemi, The third wave of asbestos disease: Exposure to asbestos in place, Annals of the New York Academy of Sciences, v. 643, p. 473-490.

Deer, W.A., Howie, R. A., and Zussman, J., 1963, Rock-forming minerals; vol. 2, Chain silicates, 379 p.: Longmans, London.

Dorling, M. and Zussman, J., 1987, Characteristics of asbestiform and non-asbestifrom calcic amphiboles: Lithos, v. 20, p. 469-489.

Drumheller, S., 2001, Libby asks state to speed superfund status: The Spokesman Review, Friday, November 23.

Goranson, R.W., 1927, Contributions from the Department of Mineralogy and Petrography, Harvard University: Aegirite from Libby, Montana: American Mineralogist, v. 12, p. 37-39.

Gunter, M.E., 1994, Asbestos as a metaphor for teaching risk perception: Journal of Geological Education, v. 42, p. 17-24.

Gunter, M.E., 1999, Quartz – the most abundant mineral in the earth's crust and a human carcinogen: Journal of Geoscinece Education, v. 86, p. 341-349.

Gunter, M.E., Brown, B.R., Bandli, B.R., Dyar, M.D., Foit, F.F., Jr., and Cornelius, S., 2003, Crystal chemistry, crystal structure, and morphology of amphibole and amphibole-asbestos from Libby, Montana U.S.A.: American Mineralogist (submitted).

Guthrie, G.D., Jr. and Mossman, B.T., 1993, Health effects of mineral dusts, 584 p.: Reviews in Mineralogy, Mineralogical Society of America, Washington, D.C.

Kane, A.B., 1993, Epidemiology and pathology of asbestos-related diseases. In G.D. Guthrie Jr., and B.T. Mossman, Eds., Health Effects of Mineral Dusts, p. 347-358: Reviews in Mineralogy, Mineralogical Society of America, Washington, D.C.

Kriegel, W.W., 1940, Summary of occurrence, properties, and uses of vermiculite at Libby, Montana: American Ceramic Society Bulletin, v. 19,p. 94-97.

Lang, H.M., 1998, A case study approach to teaching environmental mineralogy: Journal of Geoscinece Education, v. 46, p. 354-363.

Larsen, E.S., 1942, Alkalic rocks of Iron Hill, Gunnison County, Colorado: U.S. Geological Survey Professional Paper, 197A.

Larsen, E.S. and Pardee, J.T., 1929, The stock of alkaline rocks near Libby, Montana: Journal of Geology, v. 37, p. 97-112.

Leake, B.E., Woolley, A.R., Arps, C.E.S., Birch, W.D., Gilbert, M.C., Grice, J.D., Hawthrone, F.C., Kato, A., Kisch, H.J., Krivovichev, V.G., Linthout, K., Laird, J., Mandarino, J.A., Maresch, W.V., Nickel, E.H., Rock, N.M.S., Schumacher, J.C., Smith, D.C., Stephenson, N.C.N., Ungaretti, L., Whittaker, E.J.W., and Youzhi, G., 1997, Nomenclature of the amphiboles: Report of the subcommittee on amphiboles of the International Mineralogical Association, Commission on New Minerals and Mineral Names: Canadian Mineralogist, v. 35, p. 219-246.

Lockey, J.E., Brooks, S.M., Arabic, A.M., Khoury, P.R., McKay, R.T., Carson, A., Morrison, J.A., Woit, J.F., and Spitz, H.B., 1984, Pulmonary changes after exposure to vermiculite contaminated with fibrous tremolite: American Review of Respiratory Diseases, v. 129, p. 952-958.

Meeker, G.P., Bern, A.M., Brownfield, S.J., Sutley, S.J., Hoefen, T.M., Vance, J.S., and Lowers, H.A., 2003, The composition and morphology of prismatic, fibrous and asbestiform amphibole from the Rainy Creek District, Libby, Montana: American Mineralogist (submitted).

McDonald, J.C., McDonald, A.D., Armstrong, B., and Sebastien, P., 1986a, Cohort study of the mortality of vermiculite miners exposed to tremolite: British Journal of Industrial Medicine, v. 43, p. 436-444.

McDonald, J.C., Sebastien, P., and Armstrong, B., 1986b, Radiological survey of past and present vermiculite miners exposed to tremolite: British Journal of Industrial Medicine, v. 43, p. 445-449.

McDonald, J.C., McDonald, A.D., Sebastien, P., and Moy, K., 1988, Health of vermiculite miners exposed to trace amounts of fibrous tremolite: British Journal of Industrial Medicine, v. 45, p. 630-634.

Montana Department of Environmental Quality, 2000, W.R. Grace file review summary, CVID# 3726: http://deq.state.mt.us/libby/wrgracetimeline3113099.htm.

Nolan, R.P, Langer, A.M., Oechsle, G.W., Addison, J., and Colflesh, D.E., 1991, Association of tremolite habit with biological potential: Preliminary report. In R.C. Brow, J.A. Hoskins, N.F. Johnson, Eds., Mechanisms in fibre carcinogenesis, p. 231-251.

Nolan, R.P., Langer, A.M., Ross, M., Wicks, F.J., Martin, R.F., 2001, The health effects of chrysotile asbestos: contribution of science to risk-management decisions, 304p.: Special Publication #5, Mineralogical Association of Canada, Ottawa.

Pardee, J.T. and Larsen, E.S., 1929, Deposits of vermiculite and other minerals in the Rainy Creek District, near Libby, Montana: U.S.G.S., Bulletin v. 805, p. 17-28.

Ross, M., 1981, Geologic occurrances and health hazards of amphibole and serpentine asbestos: In D.R. Veblen Ed., Amphiboles and other Hydrous Pyriboles-mineralogy, p. 279-324. Reviews in Mineralogy, Mineralogical Society of America, Washington, D.C.

Ross, M., Nolan, R.P., Langer, A.M., and Cooper, C.W., 1993, Health effects of mineral dusts other than asbestos: In G.D. Guthrie Jr., and B.T. Mossman, Eds., Health

Effects of Mineral Dusts, p. 361-409. Reviews in Mineralogy, Mineralogical Society of America, Washington, D.C.

United States Environmental Protection Agency, 2000, Sampling and analysis of consumer garden products that contain vermiculite: Report 2001-S-7, United States Environmental Protection Agency, Washington D.C.

United States Environmental Protection Agency, 2001, EPA's actions concerning asbestos-contaminated vermiculite in Libby, Montana: EPA 744-R-00-010, United States Environmental Protection Agency, Washington D.C.

Weill, H., Abraham, J.L., Balmes, J.R., Case, B., Chrug, A., Hughes, J., Schenker, M., and Sebastien, P., 1990, Health effects of tremolite. American Review of Respiratory Diseases, 142, 1453-1458.

W.R. Grace, 2000, Libby asbestos time line: http://www.grace.com/mediakit/libby_asbestos_timeline.html?image=grace%20in%20the%20news.

Wylie, A.G. and Verkouteren, J.R., 2000, Amphibole asbestos from Libby, Montana: Aspects of nomenclature: American Mineralogist, v. 85, p. 1540-1542.

Zoltai, T., 1981, Amphibole asbestos mineralogy: In D.R. Veblen Ed., Amphiboles and other hydrous pyriboles - Mineralogy, p. 237-279. Reviews in Mineralogy, Mineralogical Society of America, Washington, D.C.

Tables

Table 1. Timeline of events significant to vermiculite mining operations at Libby Montana. (Note: Data obtained from Montana Department of Environmental Quality (2000) and W.R. Grace (2000).)

Year	Event
1919	E.N. Alley observes exfoliation of vermiculite in roof of mine audit
1923	Commercial mining of vermiculite begins on Vermiculite Mountain by E.N. Alley
1939	E.N. Alley's Zonolite business becomes the Universal Zonolite Insulation Company
1944	First dust control equipment installed
1948	Universal Zonolite Insulation Company changes name to Zonolite Company
1954	First "wet" mill installed at Libby mine
1956	State of Montana conducts a study to examine the working conditions at the Zonolite Company facilities in Libby
1959	State of Montana conducts a follow-up study of the 1956 study and finds dust levels are lower, but asbestos content of dust collected in the vermiculite mill is determined to be 27%
1963	W.R. Grace purchases Zonolite Company
1964	W.R. Grace begins X-ray testing of employees
1970	Occupational Safety and Health Act creates Occupational Health and Safety Administration (OSHA)
1972	First federal regulations limiting exposure of workers to asbestos are enacted by OSHA (5 fibers/cc)

1973	Clean Air Act enacted placing limits on amounts of asbestos industries can release into the environment
1974	“Dry” milling of vermiculite ore discontinued
1977	W.R. Grace initiates policy of not hiring individuals who smoke cigarettes
1977	Federal Mine Safety and Health Act enacted to create safer working environment for miners
1986	W.R. Grace receives permission to expand vermiculite mine to 1004 acres (this is the largest area the mine will cover)
1990	September: mining operations at Vermiculite Mountain end
1991	Reclamation at mine site begins
1994	W.R. Grace sells Vermiculite Mountain mine site to Kootenai Development Company
1997	Reclamation bond released on 900 acres of Vermiculite Mountain mine
1999	November, Seattle Post-Intelligencer publishes a series of articles about the high incidence of asbestos related lung disease among Libby, Montana residents
1999	November, EPA begins investigating asbestos contamination in and around Libby
2000	W.R. Grace initiates medical program to provide medical coverage for Libby residents and buys back Vermiculite Mountain mine site from Kootenai Development Company
2001	Agency for Toxic Substances and Disease Control begins health screening program for current and past Libby residents

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Table 2. Regulations for occupational exposure and environmental releases of mineral dust.

Year	Regulation	Exposure limit
1946	ACGIH	5 mppcf*
1968	ACGIH	12 fibers/cc
1972	OSHA	5 fibers/cc 8hr. TWA**
1973	Clean Air Act	Sets no specific release levels, but mandates practices for handling asbestos containing materials
1976	OSHA	2 fibers/cc 8hr. TWA
1977	Mine Act	2 fibers/cc 8hr. TWA
1986	OSHA	0.2 fibers/cc 8hr. TWA
1992	OSHA	0.1 fibers/cc 8hr. TWA, and deregulates amphibole cleavage fragments

* mppcf = millions of particles per cubic foot
** TWA = time weighted average
Note: 1946 and 1968: recommendations made by the American Conference of Governmental Industrial Hygienists. The exposure levels recommended at these times were not enforced by any regulatory agency.

Table 3. Fiber exposure estimates in fibers/ml (1: McDonald et al. 1986a, 2: Amandus et al. 1987a).

		Year						
Workstation		pre-1950	1955	1960	1965	1970	1975	1980
Dry mill	1	101.5	101.5	101.5	22.1	22.1	--	--
	2	168.4	168.4	168.4	33.2	33.2	--	--
Wet mill	1	--	--	--	--	3.9	1.5	0.8
	2	--	--	--	--	3.2	2.0	0.8
Drilling	1	--	12.5	12.5	12.5	5.2	5.2	0.8
	2	23.0	23.0	23.0	23.0	9.2	0.6	0.6
Concentrate loading	1	24.0	15.0	15.0	9.0	9.0	4.8	0.2
	2	82.5	27.7	10.7	10.7	3.2	0.2	0.2
Skip area	1	--	68.8	68.8	15.0	15.0	2.0	0.6
	2	88.3	88.3	88.3	17.4	17.4	0.6	0.6
River dock	1	--	--	12.0	12.0	12.0	12.0	0.7
	2	116.9	42.5	17.0	17.0	17.0	5.1	0.5

Figure Captions, Figures on next two pages

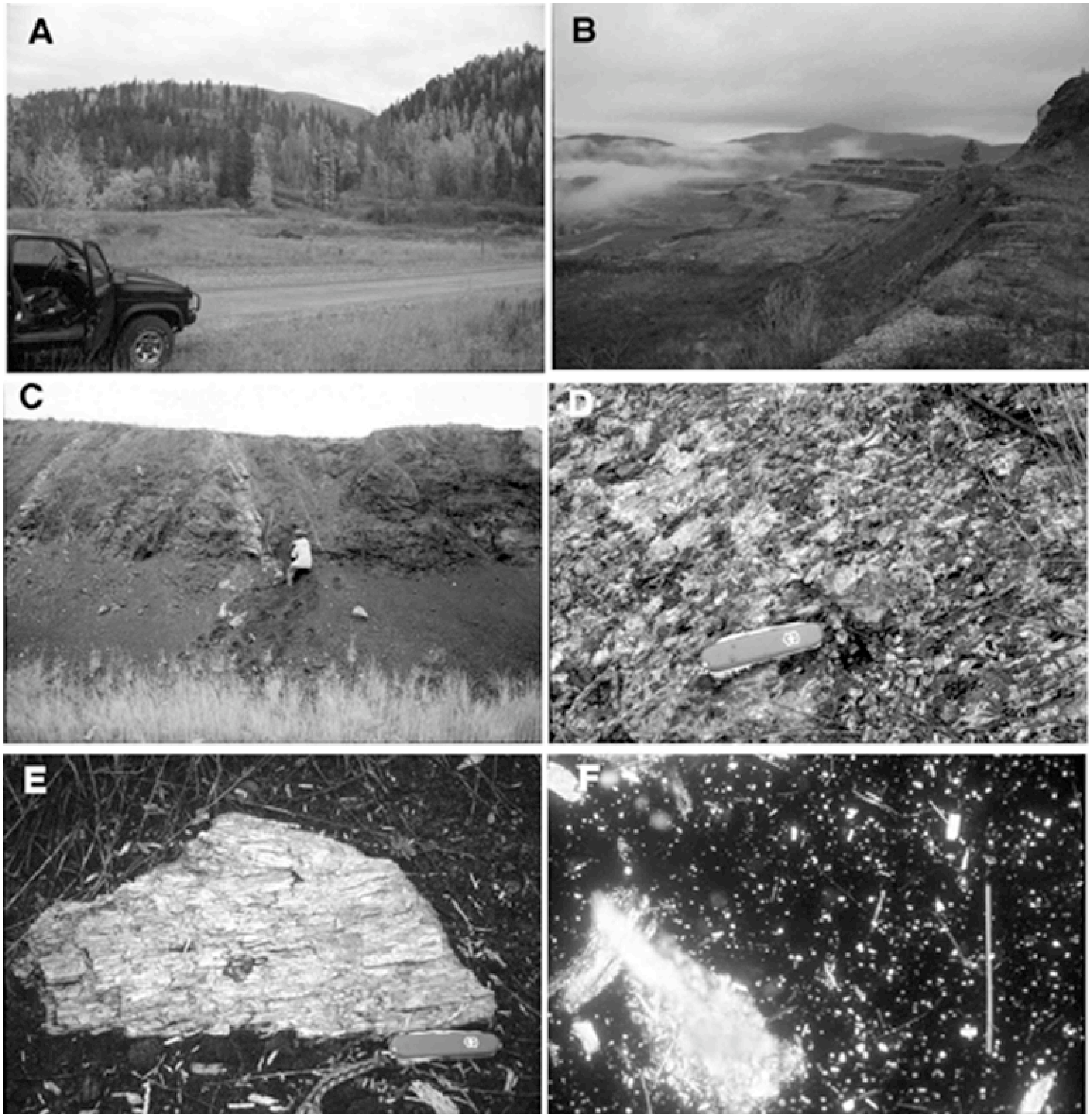
Figure 1: A. View from Rainy Creek Road east toward Vermiculite Mountain. B. View from vermiculite mountain toward Libby with mine benches visible in the middle of the photo (benches approx. 7 m. high). C. View of mine bench showing amphibole-asbestos vein (MEG for scale). D. Photograph of biotite pyroxenite. Light-colored grains are amphibole, medium-gray grains are pyroxenes, and dark-gray grains are biotite/vermiculite (knife for scale). E. Photograph of boulder composed entirely of amphibole (knife for scale). F. Photomicrograph of material from Vermiculite Mountain mine. High aspect ratio amphibole fragment (inclined extinction) visible on right side and large amphibole-asbestos fiber bundle (parallel extinction) visible in lower left corner.

Figure 2: Aerial photograph of former vermiculite mine. Photo is approximately 3 km across.

Figure 3: Map of Libby, Montana and former vermiculite mine (adapted from USEPA, 2001).

Figure 4: Photograph showing raw (unexpanded) vermiculite on left, partly expanded vermiculite at center, and completely expanded (exfoliated) vermiculite on right (cigarette lighter for scale).

Figure 5: Geologic map of RCC (adapted from Boettcher, 1966a).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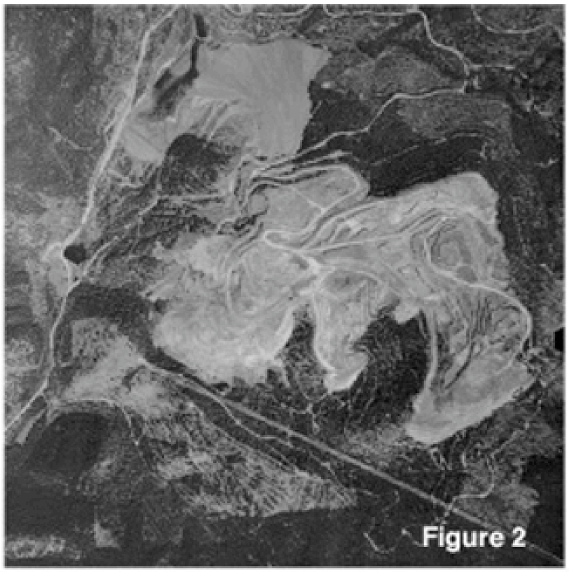
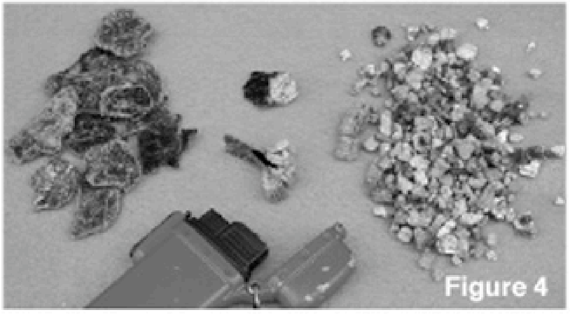


Figure 2



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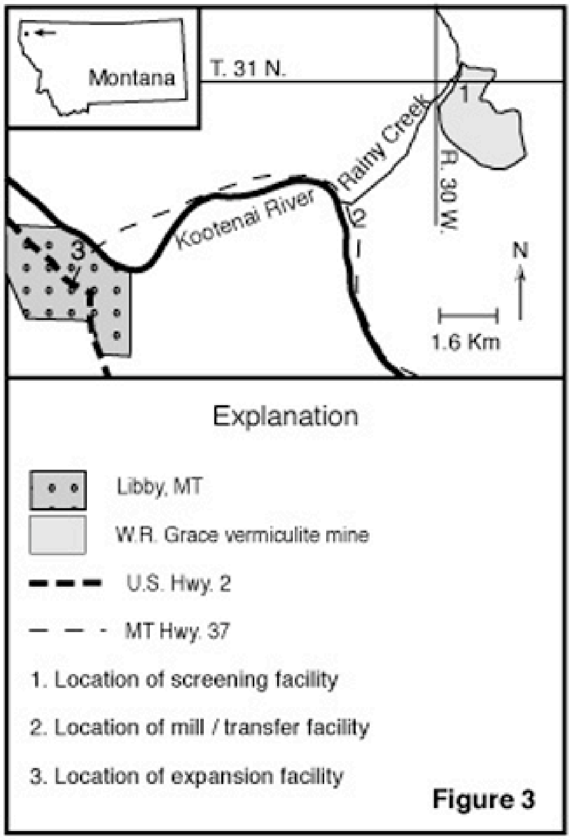

Figure 3

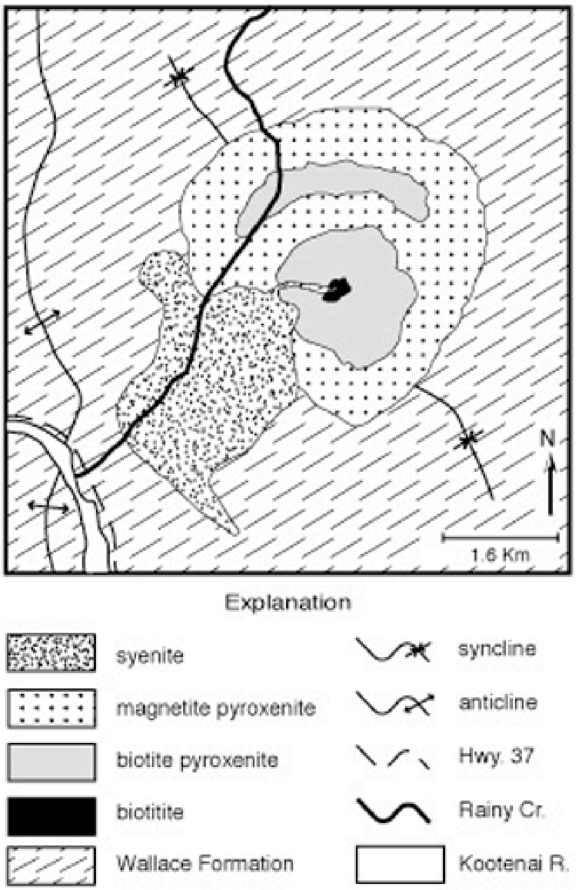

Figure 5