Preliminary Report on Using Imaging Spectroscopy to Map Ultramafic Rocks, Serpentinites, and Tremolite-Actinolite-Bearing Rocks in California

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Executive Summary

Airborne Visible/InfraRed Imaging Spectrometer (AVIRIS) data were collected in approximately 3-kilometer-wide swaths over selected areas in El Dorado and Plumas Counties that contain serpentinite and ultramafic rocks as part of an experiment to determine if potentially asbestos-bearing rocks could be identified spectrally. Mineral maps created from the AVIRIS data were used successfully to delineate exposures of serpentine and tremolite-actinolite/talc in areas with up to 70 percent vegetation cover in some cases. In other cases, the density of vegetation is so high that it prevented spectral identification by AVIRIS of minerals in those areas, thus there may be more serpentine and tremolite-actinolite/talc present than is shown on the mineral maps. It also is important to note that not all tremolite-actinolite is fibrous, and just because tremolite-actinolite was mapped, does not necessarily mean it is tremolite- or actinolite-asbestos. Finally, it is difficult to spectrally distinguish tremolite-actinolite from talc using AVIRIS. Serpentine has been detected outside of known serpentinite outcrop areas, mostly as aggregate that covers dirt roads. Four flight lines of AVIRIS data were analyzed over areas selected to show trends in degree of surface exposure as a function of elevation and vegetation cover. Field checking has verified the accuracy of the mineral maps at 25 accessible locations. Eleven additional flight lines remain to be analyzed and field checked pending future funding. AVIRIS mineral mapping has shown promise as a complement to field mapping but cannot replace it. Because AVIRIS is a remote-sensing technology, the presence of serpentine or tremolite-actinolite would have to be verified in the field by direct observation and by appropriate sampling and laboratory analysis, if needed. At this time, no conclusions regarding the presence or absence of asbestos minerals in the identified areas are possible from the AVIRIS data alone. Identification of asbestos minerals in the identified areas would require appropriate sampling and laboratory analysis of the materials in those areas.

Introduction

Naturally occurring asbestos minerals are a potential hazard to human health. Among these minerals are chrysotile (a member of the serpentine group) and the fibrous forms of several amphiboles, including tremolite and actinolite. In California, such minerals are predominantly, but not exclusively, found in serpentinite and ultramafic rocks, which are common in the Sierra Nevada, Coast Ranges, and Klamath Mountains. Correspondingly, it is important that locations of these particular types of rocks be identified and mapped so that government officials can take appropriate advisory or regulatory action to protect the public from potential exposure to naturally occurring asbestos that might result from physical disturbance of these rocks. An example of guidelines for the geological investigation of such rocks for asbestos can be found in Clinkenbeard and others (2002).

To help improve identification and mapping of rocks that may contain asbestos, the U.S. Geological Survey (USGS) and the California Geological Survey (CGS) are conducting a joint study. This study tests the effectiveness of "hyperspectral" imagery collected by the Airborne Visible/InfraRed Imaging Spectrometer (AVIRIS) to identify exposures of potentially asbestos-bearing rock, which can aid field geologic mapping of these rocks (Churchill and others, 2000). The study area consists of 16 flight lines covering narrow strips (approximately 3 kilometers wide) in El Dorado and Plumas counties in the Sierra Nevada (fig. 1). Both areas have abundant vegetation; relief ranges from low to high in El Dorado County and high in Plumas County. The AVIRIS data were collected in August 2001 over exposures of serpentinite and ultramafic rocks that were mapped during previous field studies (see Churchill and others, 2000, Churchill and Hill, 2000, and references therein). Our goal is to evaluate use of this remote-sensing technology to help identify potentially serpentine- and tremolite-actinolite-bearing rocks in areas where current geologic mapping is limited.

AVIRIS has been used in a wide variety of applications primarily because of its relatively high spectral resolution, high signal-to-noise ratio, and variable spatial scale (Green and others, 1998). This instrument, built and operated by the Jet Propulsion Laboratory for the National Aeronautics and Space Administration (NASA), is a whiskbroom scanner that can be flown aboard ER-2 or Twin Otter aircraft at altitudes ranging from 2 to 20 kilometers (km). Whiskbroom scanners collect spectra in a cross-track manner by using an oscillating mirror to sequentially reflect light from each spatial location in the scene to the spectrometer one pixel at a time. AVIRIS collects spectra in 224 continuous spectral channels covering the 0.38 to 2.5 micron wavelength range with an approximate 10-nanometer sampling interval and bandpass width (Green and others, 1998; Swayze, 2004). AVIRIS was flown on the Twin Otter platform during data acquisition over El Dorado and Plumas Counties. The use of AVIRIS for mapping rocks that potentially contain asbestos is an experimental application that is customized and not currently available "off the shelf." Collection of AVIRIS data for the 16 flight lines cost about US$38,000, while calibration, analysis, and preliminary field checking of four of the flight lines has required about a person/year of resources. As the methods initiated in this study are refined in the future, the amount of time to process and analyze AVIRIS data for this type of application should decrease.

AVIRIS Flight Line Locations

Given limited time and resources for the study, 4 of the 16 AVIRIS flight lines were selected for analysis because they had the greatest promise of testing the remote-sensing method. Flight lines chosen for analysis cover portions of Flagstaff Hill, Garden Valley, and Little Bald Mountain in El Dorado County, and Red Hill in Plumas County (fig. 1). The Flagstaff Hill line (#14) was flown N-S and includes serpentinite outcrops along the exposed low-water shoreline of Folsom Lake, near a newly constructed housing development (figs. 2A and 2B). The Garden Valley line (#7) was flown over a north-trending zone of serpentinite and ultramafic rocks, which includes the idle Garden Valley serpentinite quarry (fig. 3). The Little Bald Mountain line (#6) was flown over a N-NE-trending series of discontinuous serpentinite outcrops that stretch from Mosquito Ridge in neighboring Placer County to an area south of Georgetown in El Dorado County. This line also covers the Bear Creek serpentinite quarry (figs. 4A and 4B). The Red Hill line (#4) was flown NW-SE over the center of a massive serpentinite/ultramafic zone that is well exposed along both the North Fork of the Feather River and East Branch of the North Fork of the Feather River in Plumas County (figs. 5A and 5B). Each of the four flight lines covered serpentinite outcrops at progressively higher elevations (in the order cited above) for the purpose of studying changes in vegetative cover with varying temperature and precipitation and their effects on mapping surface mineralogy.

Methods

All 16 AVIRIS lines were collected on August 25, 2001, under clear skies within a few hours of local noon. AVIRIS was in its low-altitude configuration aboard a Twin Otter aircraft flying at or near 5300 meters (m) altitude, which produced 4-m pixels on the ground and images with swaths of about 2.5 to 3.0 km, depending on surface elevation. The data were calibrated to radiance by the Jet Propulsion Laboratory. Solar irradiance, atmospheric absorptions, and scattering were removed from the AVIRIS data using the ATREM program (Gao and others, 1993). Artifacts from the ATREM processing were removed by subtracting a path radiance correction from the data and then multiplying by correction factors derived from field spectra of a ground calibration site using the method of Clark and others (2002). A gravel parking lot along the western shore of Folsom Lake was used as the ground-calibration site. Field-reflectance measurements of this site were made with an Analytical Spectral Devices FR spectrometer on August 29, 2001. Although this site is located at 140-m elevation, the calibration derived from it also was used to correct AVIRIS data collected over the higher elevation (1930 m) Red Hill line (#4) located 110 km to the north due to a lack of calibration sites in the Red Hill area. Spectral data from each flight line (except Red Hill) were then georeferenced to USGS orthophoto quadrangles by using hundreds of well-dispersed control points and triangulation warping with nearest-neighbor resampling using commercial software.

AVIRIS data calibrated to apparent reflectance were spectrally mapped using the USGS Tetracorder System (Clark and others, 2003) version 4.1, which uses the same method as was used in mapping the World Trade Center debris (Clark and others, 2001). Tetracorder uses a modified least-squares band-shape fitting technique to spectrally identify materials and create maps of their distribution. The primary algorithm works by scaling a library spectrum to an observed spectrum using a modified least-squares solution, which derives a numerical value called "*fit*." The algorithm derives *fits* for all of the spectra in its library and selects the material with the highest *fit* as the best spectral match. In most cases, Tetracorder identifies the spectrally-dominant material in the two spectral regions where electronic and vibrational processes dominate and is capable of identifying mixtures if representative spectra of those mixtures are added to its library. When Tetracorder identifies a material as spectrally dominant, that material does not have to be pure; it also can be intimately or areally (linearly) mixed with other phases or materials (for example, serpentine plus vegetation). Spectral dominance means the diagnostic absorptions of that material are the strongest features in a given spectral region and are not obscured beyond recognition by overlapping absorptions from the other phases. Using this technique, color-coded mineral maps of the electronic (approximately 0.4 to 1.35 microns) and vibrational (approximately 1.35 to 2.5 microns) spectral wavelength regions can be produced from the flight-line data. A mineral map is an image, composed of colored pixels that represent the spatial distribution of a particular set of minerals exposed on the ground surface. Because tremolite-actinolite and serpentine minerals have their most diagnostic absorptions in the vibrational region measured by AVIRIS, we concentrated our efforts on producing mineral maps for this spectral region.

Two levels of verification were used to check the mineral maps: 1) extraction and comparison of AVIRIS spectra to reference library spectra of well-characterized minerals, and 2) mineralogic analyses of field samples. The initial spectral comparison was conducted prior to field work, thus helping to identify areas of critical concern, which later were checked in the field during September 2003. Analytical methods applied to the field samples included laboratory spectroscopy, X-ray diffraction analysis, and scanning electron microscopy (SEM).

Results

Although spectra of lizardite, chrysotile, and antigorite, are distinct from those of non-serpentine group minerals, they have similar spectral absorptions to each other in the 2 to 2.5 micron region (fig. 6). Because of this spectral similarity, chrysotile was not differentiated from the non-fibrous varieties of serpentine (for example, lizardite and antigorite) on the mineral maps. Tremolite-actinolite and chlorite have spectral signatures that are distinctly different from those of the serpentine minerals, and they can be distinguished in most cases. However, tremolite-actinolite is spectrally similar to talc with the added complication that they commonly occur together or in close proximity in altered ultramafic rocks in El Dorado County. It should be noted that not all tremolite-actinolite is fibrous, and that just because tremolite was mapped, does not necessarily mean it is tremolite- or actinolite-asbestos.

Figures 2 to 5 show mineral maps for the vibrational, spectral-wavelength region overlain on a single-channel (0.65 microns), black and white image of each flight line. Figure 2 shows chlorite, serpentine, and tremolite-actinolite/talc mineral categories for the Flagstaff Hill flight line. For figures 3, 4, and 5, only serpentine and tremolite-actinolite/talc mineral categories are shown. The tremolite-actinolite and talc were combined into a single mineralogic category at this stage of the spectral analysis because, at AVIRIS spectral resolution, differentiating between them is difficult. This aspect of the mineralogical mapping is being investigated further.

Flagstaff Hill

Figure 2A shows the mineral map over the densely vegetated Flagstaff Hill area. Most notable are exposures of serpentine plus vegetation (red) and tremolite-actinolite/talc (yellow) along roads on Flagstaff Hill. At the southern end of the hill, wide outcrops of serpentine and tremolite-actinolite/talc-bearing rocks are exposed along the northern and southern shores of the eastern arm of Folsom Lake during low-water conditions (fig. 2B). Exposures on the southern shore were field checked and spectrally verified to be chrysotile-bearing serpentinites and less-extensive fibrous tremolite-actinolite-bearing schists. Talc also is present in the schists, which tend to have a knobby texture at the hand-specimen scale due to weathering. This image also shows extensive exposures of serpentinite, and possibly tremolite-actinolite/talc, at Iron Mountain (the southern extension of Flagstaff Hill), which is currently being developed as a residential community. It was not possible to check the exposures at Iron Mountain due to restricted access to these sites.

Areas more likely to contain asbestos, as delineated by Churchill and other (2000), are shown by white lines in figures 2A and 2B. The dense clusters of pixels that represent serpentine, serpentine plus vegetation, and tremolite-actinolite/talc fall largely within these areas. At two locations marked “A” in figure 2B, the Tetracorder mineral map indicates the presence of serpentine minerals outside the area mapped by Churchill and others (2000). These spots may be, in part, fill materials and not outcrops of in-place serpentinite. During the AVIRIS flight, the low-water condition of Folsom Lake also resulted in exposure of outcrops of serpentine and tremolite-actinolite/talc that are outside of the white-line polygons shown by Churchill and others (2000). The polygons do not include this low-water exposure because they represent the higher, normal-water condition of Folsom Lake; extrapolation of these polygons across the lake likely would encompass all, or nearly all, of the low-water exposures of serpentine and tremolite-actinolite/talc shown on the mineral map.

At location “B” on figure 2B are a few small clusters of red and blue pixels along the shoreline of Folsom Lake. Although Tetracorder mapped these as serpentine and serpentine plus vegetation, field checking indicated that this area is underlain by chlorite schist. Areas “C”, “D”, and “E” were mapped as serpentine, serpentine plus vegetation, and tremolite-actinolite/talc. Examination of spectra extracted from the AVIRIS data at these sites indicates they also may be areas where chlorite was erroneously mapped as serpentine or tremolite-actinolite/talc. These localities were not field checked; therefore, resolution of these potential mapping errors will have to wait for future field investigations.

Garden Valley

Figure 3 shows the mineral map for the Garden Valley area. This line is the eastern most of three N-S flight lines oriented to cover the entire exposure of serpentinite in the area. As a result, this line only partially covers the serpentine-bearing zone, but does show the mineralogy of the idle Garden Valley serpentinite quarry. Past excavations at the quarry have exposed massive serpentinite with minor chrysotile, both of which were observed during field sampling in the fall of 2000.

There are a number of roads outside of the main serpentinite body that have the spectral signature for serpentine. Many of these roads are private, and some were field checked where they intersected public roads. In a few cases, samples of road gravel were collected on the public roads where traffic from the private roads had moved gravel onto the public roads. In each case, crushed serpentinite aggregate covering the road was observed. The “L”-shaped residential road, about 4.5 km northeast of the Garden Valley Quarry, was sampled at its intersection with a county road. X-ray diffraction (XRD) analysis of the sample indicated the presence of clinochrysotile and orthochrysotile as major constituents with trace amounts of calcite and quartz. It may be possible that lizardite, a non-asbestiform serpentine mineral, also is present because it is difficult to differentiate between clinochrysotile/orthochrysotile and lizardite based on XRD analysis alone. Figures 7A and 7B are scanning electron micrographs of fibrous chrysotile found in the sample of the residential road gravel. Chrysotile content in this sample was estimated from SEM examination to be greater than 5 percent by volume.

An area on Murphy Mountain (shown with a dashed line on figure 3 at the bottom center of the image) has a somewhat concentrated speckled pattern of pixels mapped as serpentine plus vegetation (red) and tremolite-actinolite/talc (yellow). Previous geologic mapping (Lindgren and Turner, 1894) shows this areas as underlain by a contact metamorphic zone, where plutonic rock on the southwest is intruded into metasedimentary rock on the northeast. The area is characterized by steep slopes, locally sparse vegetation (mostly grass), and bold outcrop in places. Limited field checking at the westernmost edge of this area revealed that hornblende-rich granitic soils may be one cause of this pixel pattern. This was the only site observed where tremolite-actinolite/talc may have been spectrally misidentified by Tetracorder compared to four other accessible sites on the other three flight lines, where the presence of talc and/or tremolite-actinolite was visually confirmed. The red pixels identified as serpentine plus vegetation in this area also may be due to exposures of hornblende in vegetated areas. It may be possible to eliminate this type of potential misidentification by refining the Tetracorder command file if additional field work within the main area of pixels can identify which materials are causing the spectral signatures.

Little Bald Mountain

Figure 4A shows the mineral map for the Little Bald Mountain area. Mosquito Ridge Road, at the northern end of the line, provided ready access for field checking of serpentinite and tremolite-actinolite/talc outcrops and road cuts. Most of the tremolite-actinolite/talc unit (yellow) on the mineral map represents talc schist. A thick cover of chaparral vegetation bordering this road prevented field checking for more than a few hundred meters away from the road. Poison oak, at this location and many other areas covered by the flight lines, impedes access to areas useful for field checking. Little Bald Mountain is the triangle-shaped open area surrounded by forest just north of the image's center point and is underlain by serpentinite. The Bear Creek Quarry mapped as massive and coarse-grained serpentine (blue and cyan, respectively). The quarry appeared to be idle at the time of field checking (2003).

Both within and outside of known serpentinite exposures, there are numerous roads that have serpentine spectral signatures. For example, a residential road, about 2 km south of the Bear Creek Quarry (fig. 4B), has a strong serpentine spectral signature and is located outside of the area mapped by Churchill and others (2000) as more likely to contain asbestos. Field work in 2003 revealed that this road had been paved with non-serpentinite asphalt subsequent to the AVIRIS flights, but that it originally was covered with crushed serpentinite aggregate. Narrow zones of crushed serpentinite aggregate (approximately 0.5-m wide) are still visible along margins of the road not covered by the new pavement. A small circular area, immediately adjacent to the residential road which mapped as massive and coarse serpentine, is a corral surfaced with crushed serpentinite aggregate. A north-south-trending road cut about 3 km directly north of the Bear Creek Quarry (just west of the non-forested area) has a tremolite-actinolite/talc spectral signature (fig. 4A). This segment is within one of the areas delineated by Churchill and others (2000). A check of this site was not possible during field work because it is on private property.

Red Hill

Figure 5A shows the mineral map for the Red Hill area in Plumas County. Of all the AVIRIS flight lines examined, this area has the most extensive exposures of serpentinite. The summit of Red Hill is between the North Fork of the Feather River and the East Branch of the North Fork of the Feather River (fig. 5B). Topographic relief is about 1,200 m from the East Branch canyon floor (at an elevation of approximately 750 m) to the summit of Red Hill. A small outcrop 700 m north of the "East Branch" was mapped as tremolite-actinolite/talc by Tetracorder (fig. 5B). Field checking revealed prismatic (non-fibrous) tremolite that forms porphyroblasts (large crystals) in altered ultramafic rocks. In addition to this outcrop, only a few smaller areas of tremolite-actinolite- or talc-bearing areas were detected by AVIRIS along the northern end of this flight line. Extensive outcrops of serpentinite were mapped by Tetracorder along the North Fork of the Feather River. Field checking revealed that many of these outcrops are chrysotile-bearing. These outcrops are in some cases less than 20 m from riverside campsites (fig. 5B). Soil developed on talus at the base of these outcrops may potentially contain significant quantities of chrysotile.

Additional Observations

Brief visual comparison of the Tetracorder-derived mineral maps with the areas mapped by Churchill and others (2000) as more likely to contain asbestos indicated that the high-density clusters of pixels mapped as serpentine, serpentine plus vegetation, and tremolite-actinolite/talc predominantly fall within the previously mapped areas. There are some small high-density clusters that fall outside of the previously mapped areas, but nearly all of these are within 90 to 120 m of these areas; we believe, at this time, that they may be in spatial continuity with the previously mapped areas rather than completely isolated bodies of rock material. One notable exception is the cluster of pixels mapped as serpentine west of Iron Mountain near Folsom Lake (location “A” on fig. 2B). These bodies are about 275 m from the nearest, previously mapped area of Churchill and others (2000) and may represent artificial fill. Churchill and others (2000) believed that the accuracy of the boundaries of the previously mapped areas in the El Dorado County report generally are better than plus or minus 1,000 feet.

During image analysis, it was noted that pixels mapped as serpentine plus vegetation (red) sometimes form N-S linear patterns at the transition between bright grassy fields and dark forest areas. An example of this phenomenon was field checked 1.3 km east of the Bear Creek Quarry (fig. 4B). No serpentine was found at this site. A possible explanation of this mapping artifact may be residual charge in the AVIRIS detectors where the transition from bright to dark targets causes an offset in the spectral profile for the corresponding pixels. This effect seems to be limited to N-S trending field/forest boundaries in these flight lines where the bright areas are on the west side, and the dark areas are on the east side.

Imaging spectroscopy data, such as that measured by AVIRIS, inherently have a certain level of noise that can interfere with accurate identification (Swayze and others, 2003). The effect of this noise is seen mostly as isolated random pixels that mapped as serpentine plus vegetation (red) outside of the known serpentinite/ultramafic zones. Examples of noise-induced misidentification can be seen in the central portion of the eastern one half of the Garden Valley flight line (fig. 3). Single isolated red pixels in the forest near the site marked “A” probably are misidentifications caused by random noise in the spectral data that make the vegetation spectra resemble that of serpentine plus vegetation. A general rule of thumb to use when interpreting these mineral maps is that the certainty of mineral identification goes up in a given area as the density of like-colored pixels increases. For example, the speckled red-pixel pattern surrounding “B”, in figure 3, is associated with variable vegetation cover, but the relatively high density of red pixels in this area indicates a high degree of certainty that the area is underlain by serpentine-rich rocks.

Because AVIRIS measures reflected sunlight, it cannot be used to detect minerals deeper than can be seen with the human eye, and hence the data can only provide information on surface mineralogy. Thick vegetation cover can totally obscure the ground surface preventing detection of underlying mineralogy. Computer simulations show that vegetation cover greater than approximately 70 percent can prevent spectral detection of the serpentine minerals, tremolite, actinolite, and talc if these are in their pure form. As the spectral signatures of these minerals are diluted by those of other minerals, detection of them will be prevented at even lower levels of vegetation cover within an image pixel. Consequently, any area on the images that does not have colored pixels associated with it may represent one of the following situations:

(1) It is an area that may be underlain by rocks and soil that either do not contain the types of minerals selected for mapping (for example, serpentine group minerals) or do not have sufficient amounts of these minerals to be detected using AVIRIS data.

(2) It is an area that may be underlain by rocks or soil with one or more types of minerals selected for mapping, but the density of vegetation is so high that it obscures the rocks and soil so that the minerals

cannot be detected using AVIRIS data.

These situations explain why large percentages of the areas delineated by Churchill and others (2000) do not have colored pixels associated with them (for example, Flagstaff Hill).

Pending additional funding, we will continue to process and evaluate the AVIRIS data to determine if vegetation mapping can help identify areas of underlying rock that are serpentinized.

Summary

Mineral maps derived from AVIRIS data successfully delineated areas in El Dorado and Plumas Counties where exposed rock contains serpentine and tremolite-actinolite and(or) talc. AVIRIS mineral mapping has shown promise as a complement to field mapping but cannot replace it.

Other findings:

- AVIRIS data and the Tetracorder spectral identification system were used successfully to detect serpentine and tremolite-actinolite/talc in areas with up to 70 percent vegetation cover in some cases. There also are areas along each processed flight line that may be underlain by one or more types of minerals selected for mapping, but the density of vegetation is so high that it obscures the rock and soil so that the minerals were not detected using AVIRIS data. This situation explains why large percentages of some of the areas delineated by Churchill and others (2000) do not have colored pixels associated with them.

- Serpentine has been detected outside of known exposures of serpentinite, mostly as aggregate that covers dirt roads. Aside from roads, nearly all of the high-density clusters of pixels mapped as serpentine, serpentine plus vegetation, and tremolite-actinolite/talc along the flight lines either fall inside of or are within a few hundred meters of the boundaries delineated by Churchill and others (2000).

- Limited field checking has verified the accuracy of the mineral maps. Out of 20 sites examined for the serpentine or serpentine plus vegetation map units, 17 sites were properly identified, two were not (the chlorite along the shoreline of Folsom Lake and misidentified pixels at the field/forest interface east of the Bear Creek Quarry), and one (Murphy Mountain) was inconclusive because of limited field access. Out of five sites examined for tremolite-actinolite/talc map units, only one site (Murphy Mountain) has rocks that may have been misidentified by spectral mapping. Thus, misidentifications can occur, but so far are limited in number and extent, and may be correctable in the future as the mapping method is refined.

- Future work, if funded, will focus on differentiating fibrous from non-fibrous serpentine, better spectral differentiation of actinolite, hornblende, tremolite, and talc, and software-facilitated reduction of interference by vegetative cover. Another potential task is to determine if mapping of vegetation can help delineate areas of serpentinization. Eleven additional flight lines remain to be analyzed and field checked pending future funding.

- Because AVIRIS is a remote-sensing technology, the presence of serpentine or tremolite-actinolite would have to be verified in the field by direct observation and by appropriate sampling and laboratory analysis, if needed. At this time, no conclusions regarding the presence or absence of asbestos minerals in the identified areas are possible from the AVIRIS data alone. Identification of asbestos minerals in the identified areas would require appropriate sampling and analysis of the materials in those areas.

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Glossary

<u>Actinolite</u>: A green to black Fe-bearing amphibole with the chemical formula $Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$ occupying the midrange of the tremolite-ferroactinolite compositional series. Actinolite can occur in a variety of crystal shapes and sometimes occurs as asbestiform fibers.

<u>Asbestos</u>: Asbestos is a term used for a group of silicate minerals that occur as asbestiform fibers having high tensile strength, flexibility, with heat and chemical resistance (Clinkenbeard and others, 2002).

<u>Metamorphism:</u> The process by which rocks undergo chemical or structural changes produced by increased heat or pressure, or replacement of elements by hot, chemically active fluids.

<u>Picrolite</u>: The term "picrolite" describes a vein-filling serpentine mineral that is typically pale yellow to apple green in color, and that may be either massive or pseudofibrous in habit. Because picrolite may be lizardite, chrysotile, antigorite, or a mixture of these minerals the term does not denote a particular mineral species but is a useful field term. (Clinkenbeard and others, 2002)

<u>Porphyroblasts</u>: Large mineral grains or crystals that grow during metamorphism.

<u>Serpentine</u>: A group of phyllosilicate minerals rich in magnesium and water, derived from low-temperature alteration or metamorphism of the minerals in ultramafic rocks. Serpentine minerals are light to dark green, commonly varied in hue, and greasy looking; the mineral feels slippery. It has the general formula $(Mg, Fe)_3Si_2O_5(OH)_4$. The rock-forming members of the serpentine group are non-fibrous antigorite and lizardite, and less commonly, fibrous or non-fibrous chrysotile. Chrysotile has three forms known as clinochrysotile, orthochrysotile, and parachrysotile.

<u>Serpentinite</u>: A rock composed almost wholly of serpentine minerals derived from the alteration of olivine and pyroxene. Other minor mineral constituents may include amphiboles (for example, actinolite-tremolite), brucite, chromite, magnetite, pyroxene, and talc.

<u>Tremolite</u>: A calcic amphibole with the chemical formula $Ca_2Mg_5Si_8O_{22}(OH)_2$. Tremolite can occur in a variety of crystal shapes and sometimes occurs as asbestiform fibers.

<u>Talc</u>: A magnesium phyllosilicate with the chemical formula $Mg_3Si_4O_{10}(OH)_2$. Talc can occur in foliated masses, is very soft, and has a greasy or soapy feel. Impure massive forms of talc are called soapstone.

<u>Ultramafic rock</u>: Any of a number of intrusive igneous rocks very rich in iron and magnesium and with much less silicon and aluminum than most crustal rocks. This term has been applied to describe dunite, peridotite, pyroxenite, and serpentinite rock lithologies.

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