GSA DATA REPOSITORY MATERIAL 2009183

METHODS

AVIRIS Calibration

AVIRIS has been used in a wide variety of geological and biological studies, primarily because of its relatively high spectral resolution, high signal-to-noise ratio (S/N), and variable spatial scale (Green et al., 1998). This instrument is typically flown aboard aircraft at altitudes ranging from 2 to 20 kilometers (km) and collects spectra in a cross-track manner by using an oscillating mirror to sequentially reflect light from each spatial location in a scene to a spectrometer one pixel at a time. AVIRIS collects spectra in 224 continuous spectral channels covering the 0.38 to 2.5 micron (µm) wavelength range with an approximate 10-nanometer sampling interval and bandpass width (Green et al., 1998).

AVIRIS data were corrected to apparent reflectance prior to Tetracorder mapping. Solar flux, atmospheric absorptions, and scattering were removed from the AVIRIS radiance data using the ATREM program (Gao et al., 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 et al. (2002). A gravel parking lot along the western shore of Folsom Lake was used as the ground-calibration site (see location marked in Fig. 1C). Field-reflectance measurements of this site were made with an ASD FR spectrometer® on August 29, 2001. Although the ground calibration 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 flight line, located 110 km to the north, due to a lack of ground calibration sites in the Red Hill area. Spectral data from each flight line were then georeferenced to

USGS orthophoto quadrangles using hundreds of well-dispersed control points and triangulation warping with nearest-neighbor resampling using commercial software.

Tetracorder Mapping

Tetracorder uses a modified least-squares band-shape fitting technique to spectrally identify materials or vegetation and create maps of their distribution (Clark et al., 2003). The primary algorithm works by comparing absorption features in library reference spectra to absorption features in an observed spectrum (e.g., from an AVIRIS pixel) and then calculating the linear least-squares correlation between them. The correlation coefficient is called the "*fit*." The algorithm derives *fits* for all of the spectra in its library, applies user-specified constraints on absorption features, and selects the material with the highest *fit* as the best spectral match to the observed spectrum. In most cases, Tetracorder identifies the spectrally-dominant material in the 1- and 2-µm spectral regions where electronic and vibrational processes dominate respectively; it is also capable of identifying mixtures (e.g., serpentine + vegetation) if representative spectra of those mixtures are added to its library. Maps of the distribution of various materials are assembled by assigning a unique color to pixels of each different material.

Serpentine and Tremolite Detection Thresholds

Thresholds for the spectral detection of serpentine in ultramafic rock and tremolite in serpentine were estimated from intimate mineral mixtures constructed in the lab using known quantities of reference serpentine, tremolite, and peridotite (one of the dominant ultramafic rock types found in the study areas). These mixtures were measured with an ASD spectrometer over the wavelength range from 0.35 to 2.5 µm. In this study, the S/N of AVIRIS in the 2.3-µm region, degree of vegetative cover, grain size and spectral interference of accompanying mineral phases, and grain sizes of the serpentine and tremolite control the lower threshold for detection of serpentine and tremolite. To determine the lower threshold for serpentine in ultramafic rock we extracted spectra from pixels at the edges of vegetation-free areas mapped by Tetracorder as serpentine within ultramafic units. These are areas of marginal spectral detection of serpentine, and their spectra may be used to empirically constrain the lower detection threshold of serpentine in ultramafic rocks in the Tetracorder maps. Continuum-removed band depths for the serpentine 2.33-µm band in these extracted spectra were compared to those in spectra of the laboratory mixtures. Peridotite is composed mainly of olivine and pyroxene which lack narrow absorptions in the 2.3-µm region that might hinder detection of the diagnostic serpentine absorption. AVIRIS has essentially the same bandpass as the ASD spectrometer over this wavelength range so direct comparison of continuum-removed band depths is valid. The 2.33-µm band depths in the constructed 5 and 10 weight percent (wt%) serpentine – peridotite mixtures are 4 and 7% respectively, while the band depth in the most marginal AVIRIS detection is 6%. This gives an estimate of 8 wt% serpentine in the marginal detection. Given probable grain-size and compositional variations in rocks on the ground, it is reasonable that under the best circumstances AVIRIS can be used to detect serpentine concentrations in ultramafic rocks down to about 5 to 10 wt% in vegetation-free areas with Tetracorder.

Because tremolite and serpentine both have overlapping absorptions in the 2.3-µm region, the method discussed above cannot be easily used to determine a lower detection threshold for tremolite in serpentine. Addition of a reference tremolite to serpentine in constructed mixtures results in a progressive shift of the composite absorption away from serpentine's 2.326-µm band position toward tremolite's 2.308-µm band position as tremolite content increases. Addition of 30 wt % of this same tremolite to serpentine results in a composite band centered at 2.314 µm whereas addition of 50 wt% results in composite band at 2.311 μm. Previous studies (Swayze et al., 2003; Clark et al., 2003; Clark et al., 2007) indicate that Tetracorder can be used to detect mineral band shifts of 3 nm using AVIRIS data (for band depths ~ 5%, S/N = 200). Based on this empirical data, it is likely that under favorable conditions (i.e., lack of vegetation), tremolite of this composition can be detected in serpentine down to the 10 to 20 wt% level using AVIRIS. However, as tremolite incorporates more Fe, its bands shift toward longer wavelengths (Mustard, 1992), which can hamper attempts to detect it spectrally in such low quantities in serpentine mixtures.

SPECTRAL MAP VALIDATION

The validity of Tetracorder spectral maps has been extensively field checked at nine field sites across the Western U.S. (Clark et al., 2003, Table 2) and accuracy of the algorithm was statistically modeled (Swayze et al., 2003). An accuracy assessment of the mineralogic identifications made in this study was conducted over several field seasons. Field observations of the serpentine, talc/tremolite-actinolite, and serpentine + minor dry vegetation spectral categories were made at 93 sites distributed along accessible roads, shorelines, and quarries in all five flight lines. Analytical methods used to verify the mineralogy of field samples included laboratory spectroscopy with an ASD FR spectrometer®, X-ray diffraction analysis, scanning electron microscopy, and electron probe microanalysis. Based on these reference data, the overall accuracy of the mineralogic categories was 94%. The Kappa coefficient (Congalton, 2001) was 0.91 and the confusion matrix is given in Table DR1.

Table DR1. Accuracy assessment of mineral categories.

		Field Observations			
		Minerals of interest absent*	Talc/tremolite-actinolite§	Serpentine	Serpentine + minor dry vegetation
Remote Sensing Result	Minerals of interest absent	19†	0†	0†	0
	Talc/tremolite-actinolite	2	16	0	0
	Serpentine	0	0	26	0
	Serpentine + minor dry vegetation	4	0	0	26

Overall Accuracy = 87/93 = 94%

	Producer's Accuracy	User's Accuracy
Talc/tremolite-actinolite	16/16 = 100%	16/18 = 89%
Serpentine	26/26 = 100%	26/26 = 100%
Serpentine + minor dry vegetation	26/26 = 100%	26/30 = 87%

*This category includes non-vegetated areas of rock and/or soil that do not contain serpentine, talc, tremolite, or actinolite. §There are a limited number of talc/tremolite-actinolite sites in the study areas. †Valid where the spectral signature of the surface mineralogy is not obscured by green or dry vegetation.

In June 2008, an accuracy assessment of the vegetation categories was conducted. Field observations of plant cover, in the categories of grass, chaparral, and other vegetation, and the presence or absence of serpentine, were made at 108 total points distributed along accessible roads in four of the flight lines (Garden Valley, Georgetown, Flagstaff and Cosumnes). Based on these reference data, the overall accuracy of the vegetation categories was 89%. The Kappa coefficient (Congalton, 2001) was 0.82 and the confusion matrix is given in Table DR2.

Table DR2. Accuracy assessment of vegetation categories.

		Field Observation		
		Other Materials*	Chaparral	Serpentine + major dry vegetation
Remote Sensing Result	Other Materials	48	3	5
	Chaparral	1	15	0
	Serpentine + major dry vegetation	2	1	33

Overall Accuracy = 96/108 = 89%

	Producer's Accuracy	User's Accuracy
Chaparral	15/19 = 79%	15/16 = 94%
Serpentine + major dry vegetation	33/38 = 87%	33/36 = 92%

*This category includes non-vegetated areas of non-serpentine rocks and/or soils, areas covered by green and dry vegetation without underlying serpentine rocks and/or soils, and areas covered by other non-chaparral and non-serpentine materials, such as water.

The white-polygon boundaries are an additional test of the validity of the Tetracorder spectral identifications because they are based on independently compiled geologic maps showing areas of serpentinized rock, and associated ultramafic rocks and soil. Potential mapping errors are discussed in the paragraphs below on a map-by-map basis.

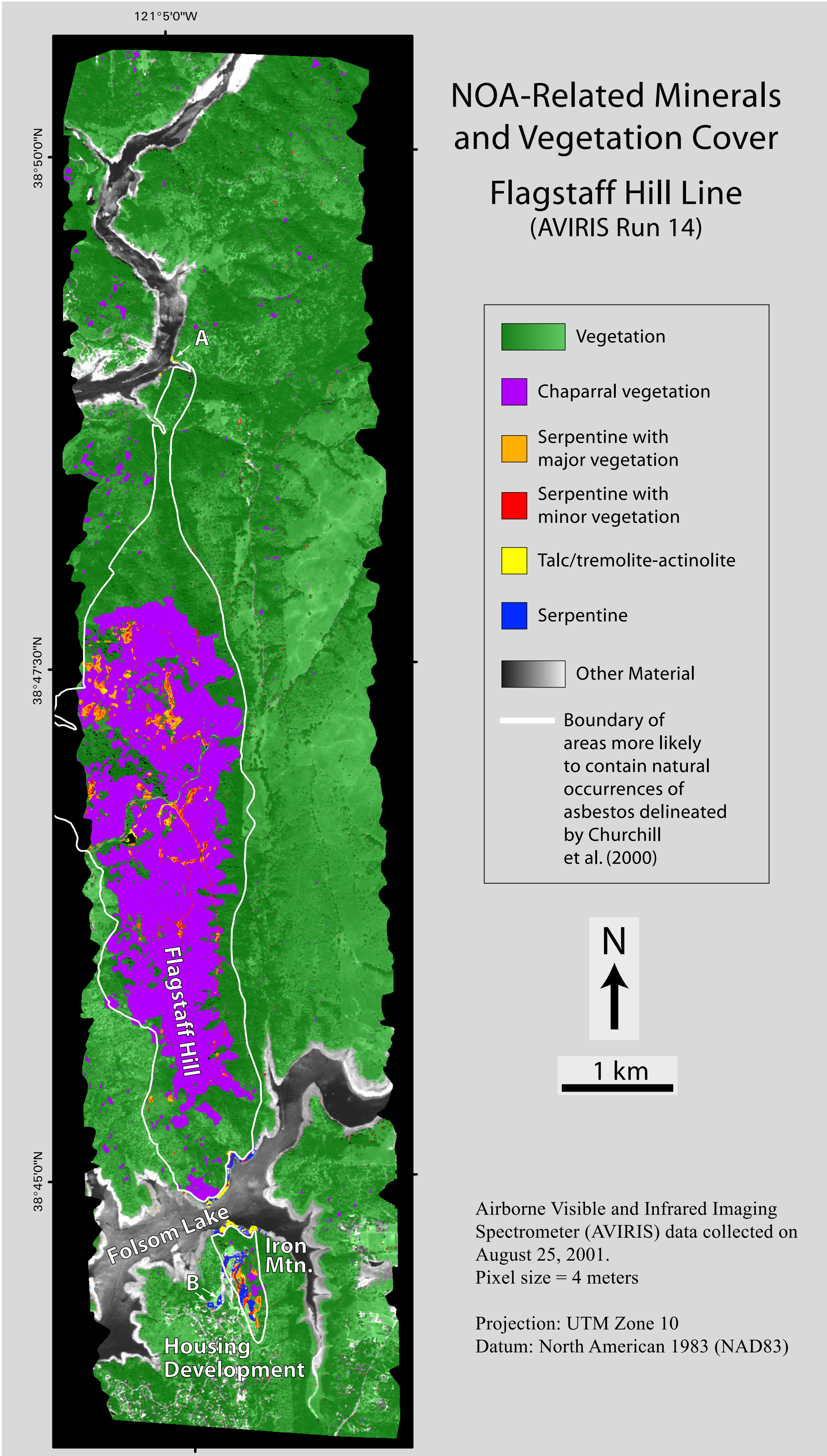
TETRACORDER MAPS AND SUPPLEMENTARY INFORMATION

Flagstaff Hill

Figure DR1 shows the entire Flagstaff Hill map. The cluster of yellow pixels marked "A" in Figure DR1, just outside of the extreme northern end of the white-line polygon area, was field checked and the presence of talc and tremolite-actinolite was confirmed by visual inspection and scanning electron microscope energy dispersive (SEM-EDS) analyses. This map also shows extensive exposures of serpentine, and possibly talc/tremolite-actinolite (T/TA), at Iron Mountain – a location recently developed as a residential community. The white polygons do not include the low-water exposures of serpentine and T/TA seen on the AVIRIS maps because they represent the higher, normal-water condition of Folsom Lake; extrapolation of these polygons across the lake likely would encompass nearly all of the low-water exposures of the minerals shown on the map. It was not possible to check exposures at Iron Mountain due to restricted access to these sites. At two locations marked "B" in the southern-most portion of Figure DR1, the map indicates the presence of serpentine minerals outside the area mapped by Churchill et al. (2000). These spots may be construction fill materials and not exposures of *in-situ* serpentinite.

Serpentinized-ultramafic rock and tremolite-talc schist crop out along the Folsom Lake shoreline south of Flagstaff Hill and north of Iron Mountain (Figs. 2C and DR1). These rock units are surrounded by metavolcanic rocks rich in magnesiohornblende, which was spectrally confused with tremolite and talc during the initial stages of Tetracorder mapping. Magnesiohornblende is spectrally similar to tremolite and talc in the 2.0 to 2.5-µm region, but it has a 2.25-µm absorption (possibly due to vibration of a non-tetrahedral Al-OH bond) that is found only weakly in spectra of fibrous tremolite from Flagstaff Hill and is not present in spectra of talc (Fig. 2A). The presence of

Figure DR1. Flagstaff Hill NOA-related minerals and vegetation cover (AVIRIS line 14). Area labeled “A” contains talc and tremolite/actinolite. Areas labeled “B,” which were spectrally mapped as serpentine, are outside of the area more likely to contain asbestos as delineated by Churchill et al. (2000) and may be fill placed there for building pads.



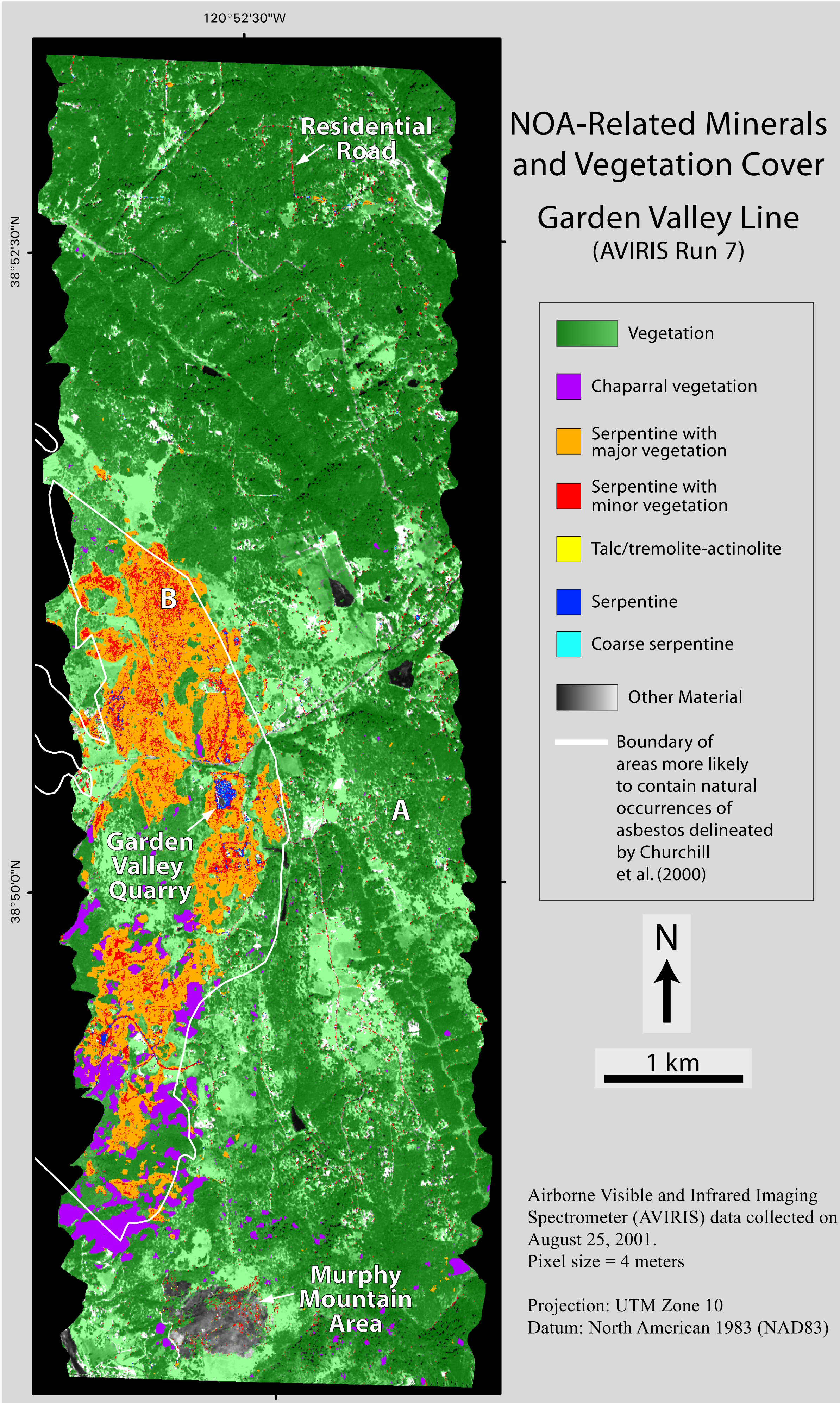
this 2.25-µm absorption and a 9 nm shift of magnesiohornblende's main 2.32-absorption toward longer wavelengths relative to those of tremolite and talc, were used to spectrally differentiate between these minerals in the final stages of Tetracorder mapping.

Garden Valley

Figure DR2 shows the entire map for the Garden Valley area. This AVIRIS 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 serpentine quarry. Past excavations at the quarry have exposed massive serpentine with minor chrysotile, both of which were observed during field sampling in the fall of 2000.

Imaging spectroscopy data, such as that measured by AVIRIS, inherently have a certain level of noise that can interfere with accurate identification of materials (Swayze et al., 2003). The effect of this noise is seen mostly as isolated random pixels that mapped as serpentine + minor dry vegetation (red) outside of the known serpentinite/ultramafic zones. Examples of noise-induced misidentification can be seen in the central portion of the eastern half of the Garden Valley map (Fig. DR2). 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 + minor dry vegetation. A general rule of thumb to use when interpreting these maps is that the certainty of mineral identification increases in a given area as the density of like-colored pixels increases. For example, the speckled red-pixel pattern surrounding "B", in Figure DR2, 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

Figure DR2. Garden Valley NOA-related minerals and vegetation cover (AVIRIS line 7). Single isolated red pixels in the forest near "A" are probably misidentifications caused by noise in the spectral data. The speckled red-pixel pattern surrounding "B" is caused by partially vegetated exposures of serpentinized rock.



rocks.

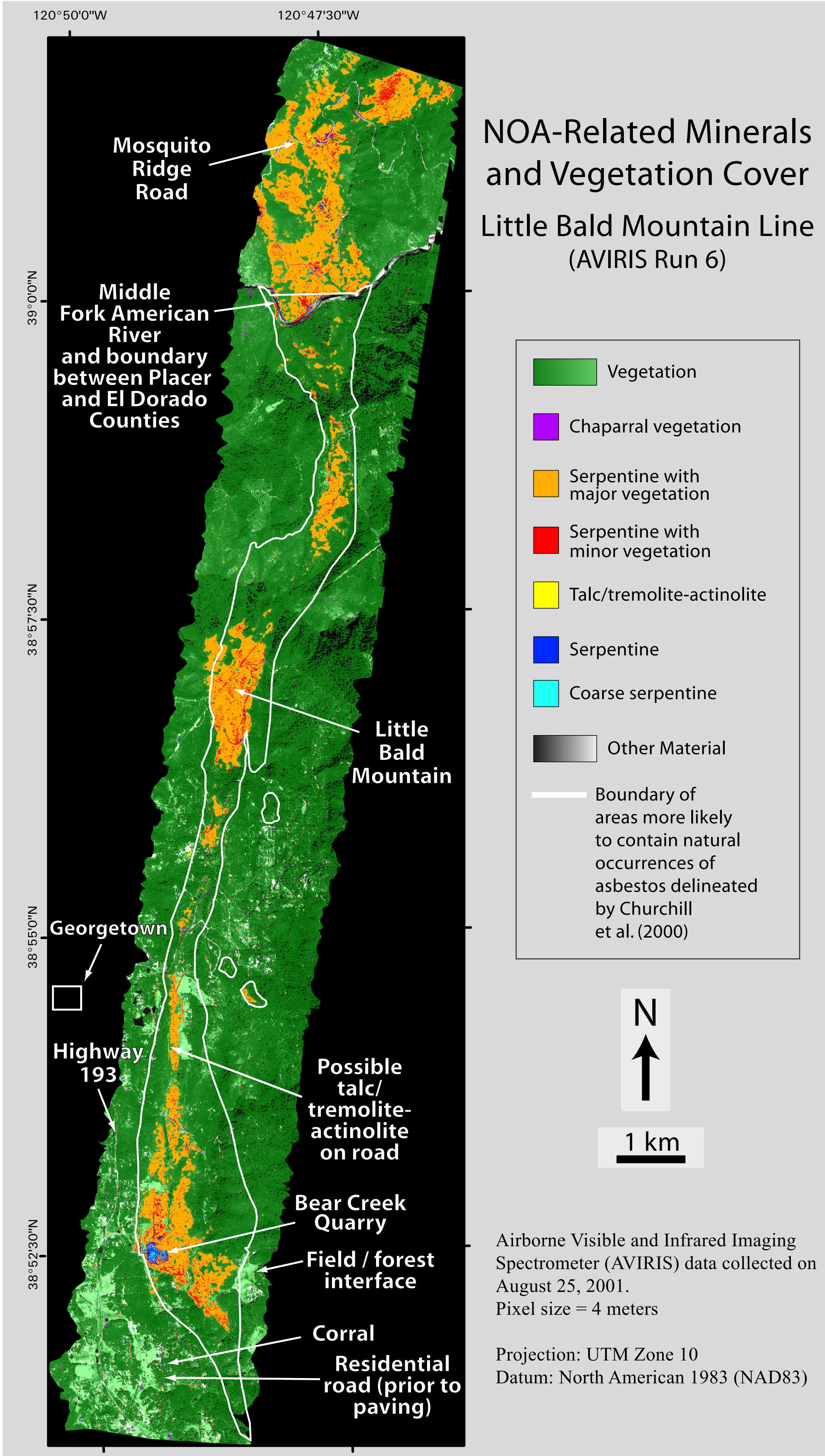
An area on Murphy Mountain (Fig. DR2 at the bottom center of the map) has a speckled pattern of pixels mapped as serpentine + minor dry vegetation (red) and a few scattered (yellow) pixels mapped as T/TA. Previous geologic mapping (Lindgren and Turner, 1894) shows that this area is underlain by a contact metamorphic zone, where plutonic rock (granite) on the southwest is intruded into metasedimentary rock on the northeast. The area is characterized by steep slopes, locally sparse vegetation (mostly grass), and patchy outcrops. This area appears to have been recovering from a brush fire at the time of the AVIRIS overflight during the summer of 2001, as indicated by a characteristically black area on a color-composite of the AVIRIS data (not shown). Field checking in 2005 did not reveal any serpentine, but did reveal that the granite contains amphiboles similar to the magnesiohornblende-actinolite assemblage found near Iron Mountain on the Flagstaff Hill map. The red pixels identified as serpentine + minor dry vegetation in this area are probably due to black lichen rock coatings (possibly charred by the fire), which spectrally mimic the shape of the serpentine 2.33-μm absorption. The few pixels of T/TA may correspond to areas on the ground where granite, containing magnesiohornblende crystals, crop out. There is another confirmed burned area located in the northwestern portion of the Red Hill AVIRIS line on previously mapped (Mayfield and Day, 2000) serpentinite/ultramafic rocks (Fig. DR5). A possible burned area is located in the northeastern corner of the Cosumnes River AVIRIS line (Fig. DR4). Field checking is necessary to confirm the presence of spectrally detected serpentine and T/TA in burned areas.

Little Bald Mountain

The Little Bald Mountain AVIRIS line was flown over a N-NE-trending series of discontinuous serpentinite outcrops that extend from Mosquito Ridge in neighboring Placer County to an area south of Georgetown in El Dorado County. Figure DR3 shows the spectral map for the Little Bald Mountain area. Mosquito Ridge Road, at the northern end of the line, provided access for field checking of serpentine and T/TA outcrops and road cuts. Most of the yellow pixels on the map represent talc schist. Little Bald Mountain is the triangle-shaped open area surrounded by forest just north of the map's center point; it is underlain by serpentinite. The Bear Creek Quarry mapped as massive and coarse-grained serpentine (blue and cyan, respectively), and it appeared to be idle at the time of field checking (2003).

There are several roads that have serpentine spectral signatures both within and outside of known serpentinite exposures. For example, a residential road, about 2 km south of the Bear Creek Quarry (Fig. DR3), has a strong serpentine spectral signature and is located outside of the area mapped by Churchill et al. (2000) as more likely to contain naturally occurring asbestos (NOA). Field work in 2003 revealed that this road had been paved with non-serpentine-bearing asphalt subsequent to the AVIRIS flights, but that it originally was covered with crushed serpentine aggregate (during the AVIRIS overflight). Narrow zones of crushed serpentine aggregate (approximately 0.5-m wide) are still visible along margins of the road that are 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 serpentine aggregate. A N-S-trending road cut about 3 km directly north of the Bear Creek Quarry (just west of the non-forested area) has a T/TA spectral signature. This segment is within one of the polygons delineated by Churchill et al. (2000). It was not possible to check this road cut due to restricted access.

Figure DR3. Little Bald Mountain NOA-related minerals and vegetation cover (AVIRIS line 6).



Cosumnes River

The Cosumnes River AVIRIS line was flown over a N-S-trending series of serpentinite outcrops along the East Bear Mountains Fault in southern El Dorado County (Fig. 1), which continue south into neighboring Amador County. Figure DR4 shows the map for the Cosumnes River AVIRIS line. Because the Churchill et al. (2000) study focused on El Dorado County, the white-polygon lines marking areas more likely to contain NOA do not extend across the Cosumnes River south into Amador County. At the bottom left of Figure DR4, mapping shows a NW-trending area of serpentine + dry vegetation. Fieldwork confirmed the presence of serpentine in this area. This is one of the better examples where the use of AVIRIS, for mapping NOA, has found an area of serpentinized ultramafic rocks not shown on published geologic maps of the area.

At the bottom right of Figure DR4, mapping shows a small area (color-coded yellow) with a strong T/TA spectral signature. Field investigation indicates this area coincides with a dry stock pond (at least at the time of the AVIRIS flight) built on a geologic contact between ultramafic and metaconglomerate rocks. Although it was not obvious in the field, samples of dry mud from the stock pond contain talc and asbestiform tremolite-actinolite based on laboratory spectroscopic measurements and SEM-EDS analyses. This example demonstrates how AVIRIS spectral mapping can be used to augment field work.

Red Hill

The Red Hill line was flown NW-SE over the center of a massive serpentinite/ultramafic zone that is well exposed along both branches of the North Fork of the Feather River. Figure DR5 shows the map for the Red Hill area in Plumas County. Of all the AVIRIS flight lines examined, this area has the most extensive exposures of serpentine. The summit of Red Hill is between the

Figure DR4. Cosumnes River NOA-related minerals and vegetation cover (AVIRIS line 12).

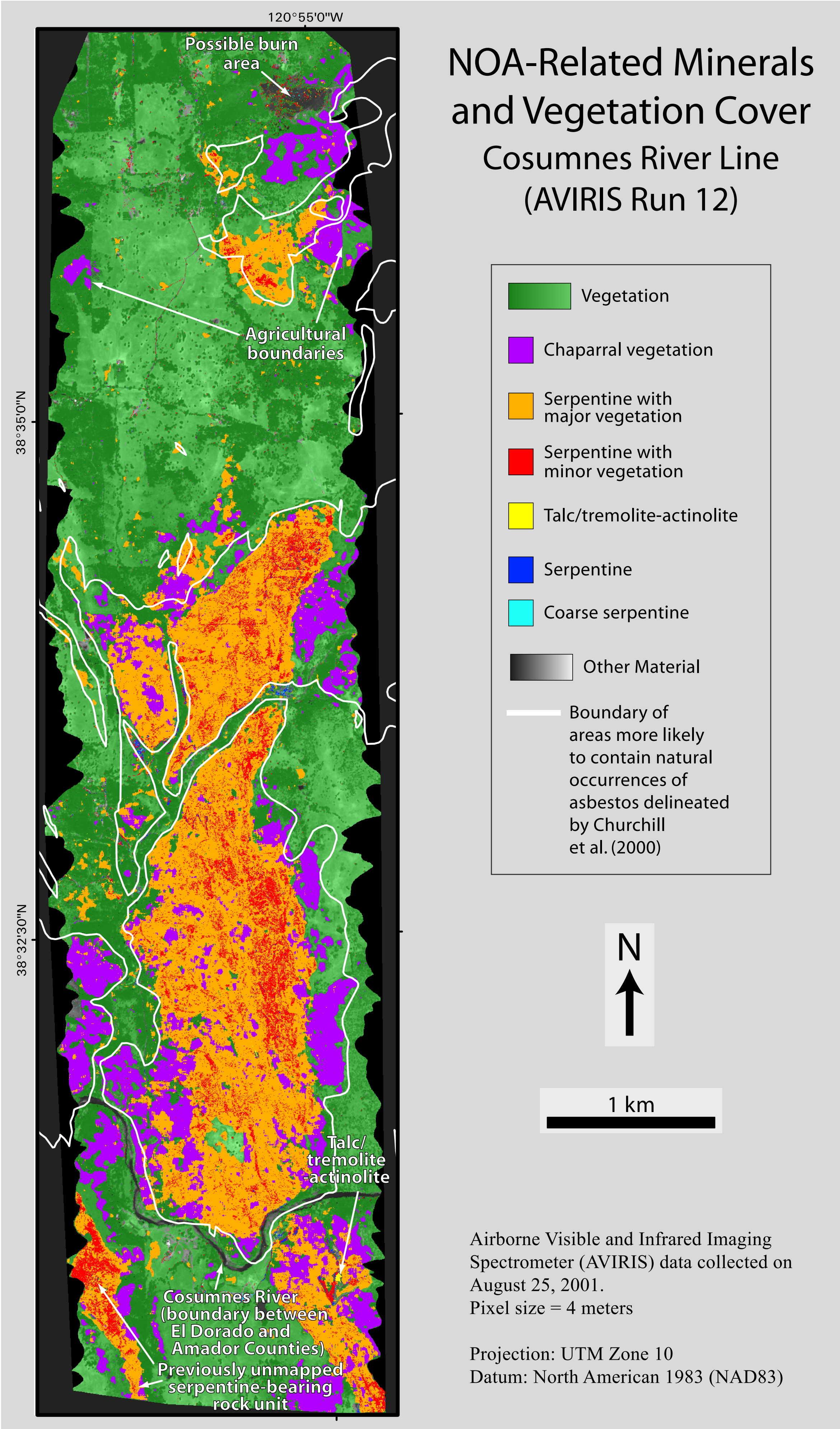
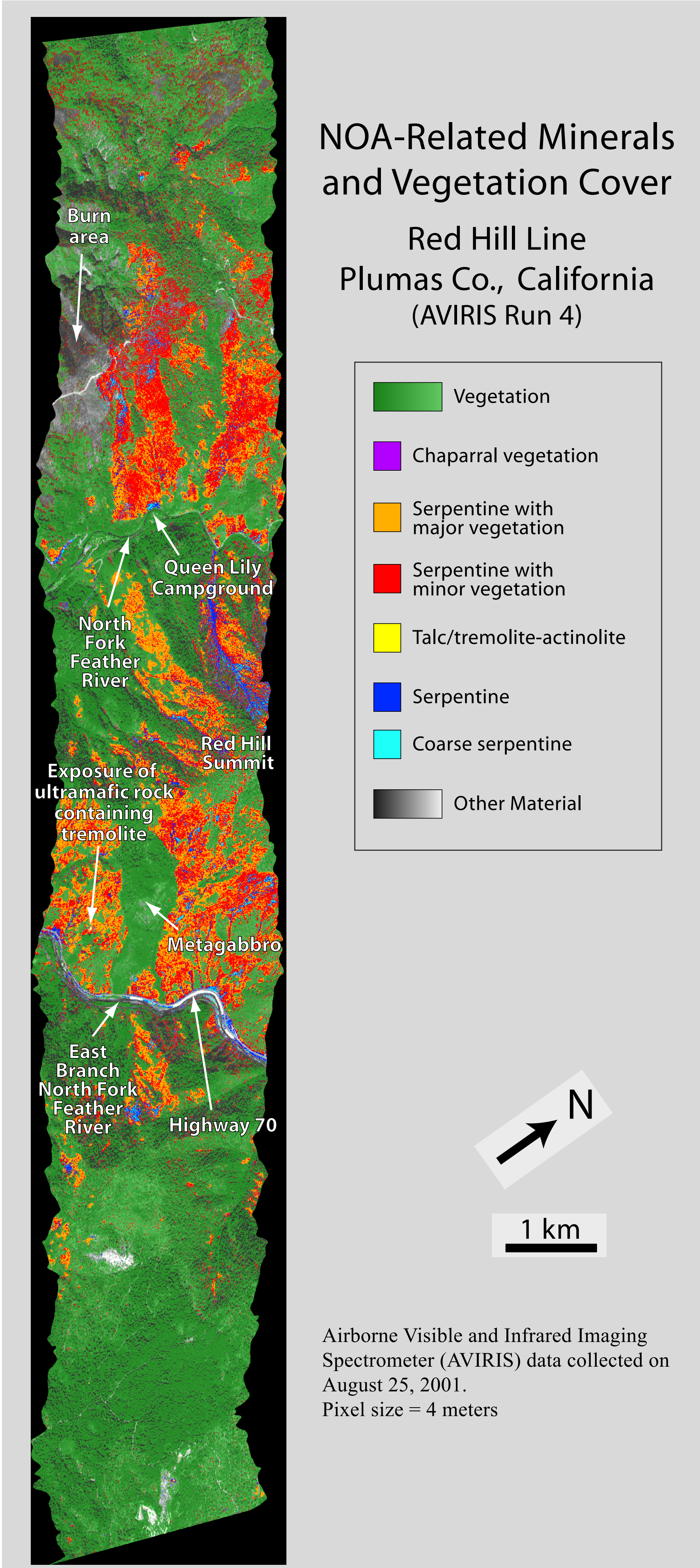


Figure DR5. Red Hill NOA-related minerals and vegetation cover. Image is not georeferenced and does not have latitude and longitude marks (AVIRIS line 4).



Airborne Visible and Infrared Imaging Spectrometer (AVIRIS) data collected on August 25, 2001.
Pixel size = 4 meters

North Fork of the Feather River and the East Branch of the North Fork of the Feather River. 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 spectrally mapped as T/TA (Fig. DR5). Field checking revealed prismatic (non-fibrous) tremolite porphyroblasts in altered ultramafic rocks at that location. Extensive outcrops of serpentine were spectrally mapped along the North Fork of the Feather River. Field checking revealed that many of these outcrops are chrysotile-bearing.

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