Remote Mineralogic and Lithologic Mapping of the Ice River Alkaline Complex, British Columbia, Canada, Using AVIRIS Data

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Abstract

The Ice River Alkaline Complex is a late Paleozoic intrusion of mafic alkaline rocks, syenite, and carbonatite exposed in southeastern British Columbia, Canada. The complex intrudes Cambrian and Ordovician shales, slates, and limestones of the Chancellor and Ottertail Formations and the McKay Group. We examined the alkaline complex and adjacent country rocks using Airborne Visible-Infrared Imaging Spectrometer (AVIRIS) data. The data were first calibrated to relative reflectance and then used to spectrally map mineralogies in the study area by using a linear spectral unmixing program. This technique models each pixel spectrum in an AVIRIS image as a linear combination of unique endmember spectra. We selected endmember spectra from well-exposed and spectrally distinct mineralogic units, vegetation, and snow. Four of the endmembers reflect mineralogic variations within the McKay group in the study area, and may represent lateral and vertical variations of sedimentary or metamorphic facies. Otherwise, the resultant spatial distribution of endmembers shows generally close agreement with the published geologic map, although, in several places, our image-map is more accurate than the published map.

Introduction

The Ice River Alkaline Complex is a V-shaped exposure of alkaline rocks located 25 km south of Field and 40 km east-southeast of Golden, British Columbia, Canada (Figure 1). The maximum northwest-southeast dimension of the complex is about 12 km. Most of the complex is exposed along two ridges within the Ottertail Range that are separated by the Ice River valley. The main body of the complex is exposed along a ridge extending between Sentry Peak and Mount Mollison east of the Ice River, and along the eastern slopes of Eagle Ridge west of the Ice River (Figure 1). A smaller portion of the complex crops out at the head of Moose Creek east of the main complex.

Topography in the area is the result of Pleistocene glaciation and is characterized by sharp aretes separated by U-shaped valleys. Elevations range from 1500 m to 3500 m. Timberline is at about 2400 m, and very little bedrock is exposed below 2300 m. Above timberline, however, rock exposure is almost complete.

This area was selected as part of ongoing studies in the application of remote sensing techniques for compositional mapping of alkaline rock/carbonatite intrusive complexes.

These complexes are interesting because of their rare petrologic associations and their economic value as hosts to rare-earth elements (REEs) and other commodities commonly associated with carbonatites.

This report focuses on the northwesterly extension of the complex and the adjacent country rocks west of the Ice River along Eagle Ridge (Figures 1 and 2). We describe an application of imaging spectrometry to mineralogic and lithologic mapping using Airborne Visible-Infrared Imaging Spectrometer (AVIRIS) data acquired on 22 August 1990, from a NASA ER-2 aircraft flying about 18,200 m above mean ground elevation. The AVIRIS instrument collects spectral radiance data in 224 channels in the portion of the electromagnetic spectrum from 0.4 to 2.5 µm (Vane et al., 1993). Each AVIRIS image segment depicts an area of about 10 km by 8 km and has a ground (pixel) resolution of 16 to 20 m.

Laboratory visible-infrared (0.4 to 2.5 µm) reflectance spectra of both weathered and fresh surfaces of field samples were recorded digitally on a Beckman Instruments Model UV5240 spectrophotometer equipped with an integrating sphere.[1] The spectra were corrected for minor measurement errors introduced by the instrument and for weak absorption features in the halon reference material (Crowley et al., 1986). The mineralogic interpretations of these spectra were supported by X-ray diffraction analysis.

Lithology and Spectral Reflectance of Field Samples

The Ice River complex is late Paleozoic in age and intruded Cambrian and Ordovician shales and limestones in two phases (Currie, 1975). During the first phase, a complexly layered, mafic, sill-like body intruded the country rock. The second phase resulted in the intrusion of a syenite stock that cuts vertically across the layered sill. A carbonatite plug is exposed within the layered sill, and associated carbonatite veins and dikes are present within the sill and syenite stock. However, the exact timing of the emplacement of these carbonatite rocks is not clear (Currie, 1975).

Country Rocks

The country rocks that host the complex are regionally and contact metamorphosed shales and limestones of the Cam-

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[1] Any use of trade, product, or firm names in this publication is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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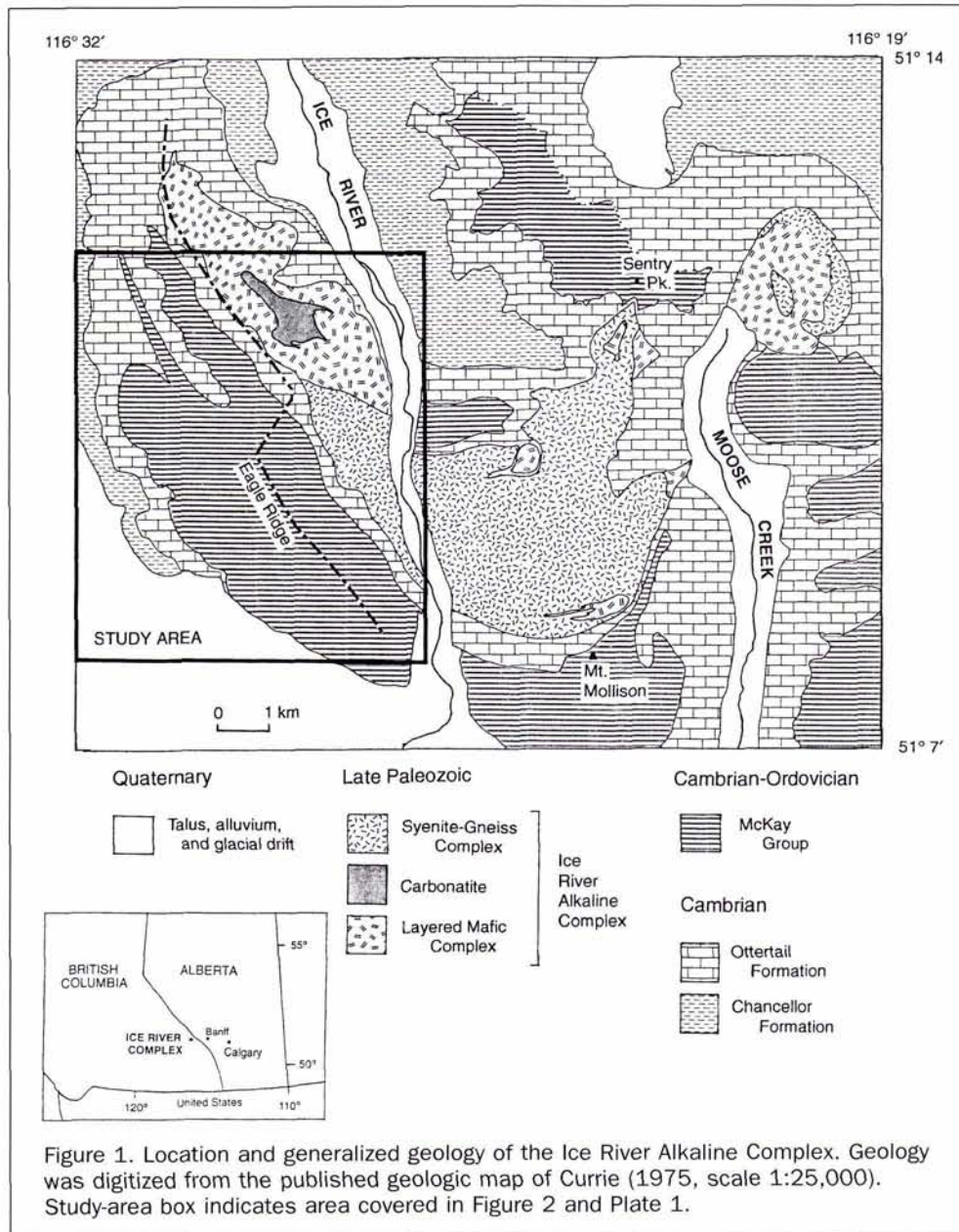
Figure 1. Location and generalized geology of the Ice River Alkaline Complex. Geology was digitized from the published geologic map of Currie (1975, scale 1:25,000). Study-area box indicates area covered in Figure 2 and Plate 1.

brian Chancellor and Ottertail Formations and upper Cambrian and lower Ordovician McKay Group (Currie, 1975) (Figure 1).

Chancellor Formation
The Chancellor Formation consists of calcareous shales in the lower part and reddish slate interbedded with dolomite or siliceous limestone in the upper part (Currie, 1975). These rocks have undergone low-grade regional metamorphism and contain large amounts of sericite and lesser amounts of biotite and chlorite. In our study area, the Chancellor is not exposed above timberline and no field samples were collected. The contact between the Chancellor and the overlying Ottertail Formation is gradational (Currie, 1975).

Ottertail Formation
The Ottertail Formation consists predominantly of massive limestone with shaley horizons near the base, which mark the transitional contact with the underlying Chancellor Formation. The Ottertail is almost pure calcite but has minor amounts of

insoluble residue consisting of argillaceous material and quartz, with minor tremolite and muscovite in siliceous layers, which indicate a moderate degree of metamorphism (Currie, 1975). The Ottertail Formation is exposed along Eagle Ridge in the northern part of the study area and on the eastern slopes of Eagle Ridge in the south (Figure 1).

Reflectance spectra of limestone of the Ottertail are relatively flat, except for a weak to moderately intense carbonate (CO_3) absorption feature at 2.33 μm (Hunt, 1977) (A, B; Figure 3a). In some samples, the shape of the carbonate feature is modified by an absorption feature at 2.30 μm caused by tremolite (C; Figure 3a). Spectrum C also has weak absorption features at 1.4 μm and 2.34 μm because of the presence of chlorite (Hunt, 1977).

McKay Group
Rocks of the McKay Group, which is undifferentiated in this area, consist of alternating layers of slate, siliceous slate, and siliceous limestone (Currie, 1975). The rocks are substantially metamorphosed and contain biotite, chlorite, and cli-

Figure 2. Grey-scale image of AVIRIS band 17 (0.557 μm) in the study area.

(a)

(b)

Figure 3. (a) Laboratory reflectance spectra of representative field samples of the Ottertail Formation (A-C) and Mc-Kay Group (D-F). Reflectance values for each spectrum at 1.7 μm are A, 39%; B, 38%; C, 28%; D, 63%; E, 37%; and F, 27%. All spectra were measured on weathered surfaces except for C, which was measured on a fresh surface. (b) Laboratory reflectance spectra of representative field samples of ijolite (A and B) and carbonatite (C-E). Reflectance values for each spectrum at 1.7 μm are A, 18%; B, 11%; and C-E, 38%. Spectra A, B, and D were measured on weathered surfaces, while spectra C and E were measured on fresh surfaces. All spectra are offset vertically for clarity.

nozoisite. The McKay Group is exposed along the western slopes of Eagle Ridge in the northern part of the study area, and on both sides of Eagle Ridge in the south (Figure 1).

Reflectance spectra of samples from the northern part of the study area exhibit the Al-OH absorption of muscovite centered near 2.20 μm, and Mg-OH absorption near 2.35 μm caused by chlorite (Hunt, 1977) or, in some cases, biotite and clinozoisite (D; Figure 3a). The more intense 2.33 μm feature in some samples is caused by CO_3 absorption in calcite (E; Figure 3a). In other samples, features are significantly subdued and the spectra are nearly flat. A thin sub-unit at the base of the McKay is iron stained, and the spectra exhibit Fe^{3+} absorption between 0.75 μm and 1.1 μm because of the presence of goethite (Hunt, 1977), with a minor Mg-OH absorption feature at 2.35 μm caused by chlorite (F; Figure 3a).
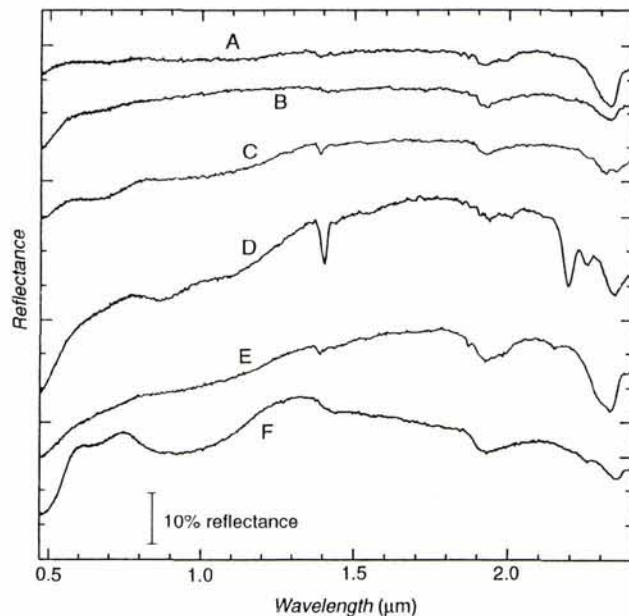
Alkaline Complex
The alkaline rocks of the complex have been divided into three main compositional components: (1) layered mafic complex, (2) syenite-gneiss complex, and (3) carbonatite plug (Currie, 1975) (Figure 1).
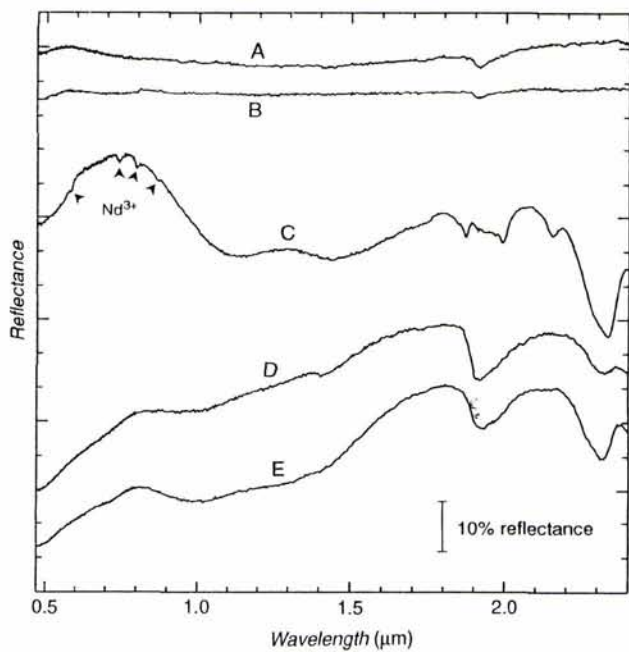
Layered Mafic Complex
The layered mafic complex consists of a poorly developed but intricate layering of jacupirangite, ijolite, and urtite. Ijolite is volumetrically the largest component of the layered complex in our study area and is exposed along the eastern slopes of Eagle Ridge (Figure 1). The ijolite consists of nepheline and pyroxene in equal amounts, and sphene and apatite occur as accessory minerals (Currie, 1975). Carbonate minerals are also present as accessories in all units of the layered complex and occur as small veins and dikes.

Syenite-Gneiss Complex
The syenite-gneiss complex constitutes the bulk of the outcrop in the entire complex and consists of nepheline syenite,

which is vaguely to distinctly gneissic and ranges from mesocratic to leucocratic (Currie, 1975). Most of the syenite complex is exposed along a ridge between Mount Mollison and Sentry Peak east of Ice River. Only a small extension of the complex is present within our study area along the eastern slopes of Eagle Ridge (Figure 1).

The spectra of ijolite (A, B; Figure 3b) and nepheline syenite are flat and featureless because these rocks do not contain significant amounts of hydrous and carbonate minerals. However, this shape does make the rocks spectrally distinctive, because the spectra of all other units in the area do show absorption features.

Carbonatite

The composition of the carbonatite ranges from almost pure calcite to ankerite (Currie, 1975). The carbonatite locally contains large amounts of pyrite, which, upon weathering, produces iron oxides that impart a red-brown surface color. On fresh surfaces, the color ranges from nearly white to brown. The plug crops out in the central portion of the eastern slopes of Eagle Ridge (Figure 1). Although a portion of the plug does crop out above timberline, it is extensively covered by grass and soil.

The spectra of the carbonatite are characterized by moderate to intense CO_3 absorption between 2.31 μm and 2.33 μm (C-E; Figure 3b). X-ray diffraction analysis revealed that most of our field samples were dolomitic, which accounts for the absorption feature centered near 2.31 μm (D and E; Figure 3b). Most of the spectra have a broad Fe^{2+} feature between 0.80 μm and 1.30 μm caused by substitution of ferrous iron for magnesium in dolomite (Rowan et al., 1986). Unlike other carbonatite/alkaline rock complexes (e.g., Mountain Pass, California, and Oka, Quebec, Canada), the carbonatite at Ice River is not very enriched in REEs. However, one of our samples (C; Figure 3b) did display minor absorption features located at 0.58, 0.74, 0.80, and 0.87 μm, which are characteristic of neodymium absorption (Rowan et al., 1986).

Analysis

Calibration of the AVIRIS Data

The first step in calibration was to perform a first-order correction for atmospheric absorption and scattering by using the atmospheric radiative transfer model implemented in the Atmospheric Removal Program (ATREM) software (CSES, 1992b). In this model, the amount of atmospheric water vapor is calculated on a pixel-by-pixel basis using a three-channel ratio technique around the water absorption features at 0.94 μm and 1.14 μm in an AVIRIS spectrum (Gao et al., 1993). These water vapor values are then used to model the water vapor and other gaseous absorption effects in each band of the AVIRIS data and derive scaled surface reflectance.

The second step was to apply a ground target calibration to correct for residual spectral anomalies in the ATREM corrected data. To do this, nine laboratory spectral measurements of ijolite samples collected from the area between the carbonatite plug and the Ottertail Formation (Figure 1) were averaged. This average was then divided by a 50-pixel average spectrum extracted from the same area in the AVIRIS image. This produces a multiplier for each channel of data that is then applied to each pixel in the channel and scales the data to surface reflectance.

Compositional Mapping

Several workers have shown the utility of imaging-spectrometer data for mineralogic mapping in arid regions (e.g., Clark et al., 1992; Crowley, 1993; Kruse et al., 1993; Boardman and Kruse, 1994). They have used several recently developed methods designed specifically for the analysis of this type of

data. These methods include (1) least-squares band-fitting, which quantitatively compares the degree of fit between image spectra and reference spectra (Clark et al., 1992); (2) spectral angle mapper (SAM), which calculates the vector angle between individual image spectra and reference spectra (CSES, 1992a); and (3) linear spectral unmixing, which models each pixel spectrum as a linear combination of "endmember" spectra (Boardman, 1991). An endmember spectrum is a compositionally and spectrally unique component of the image.

We selected the linear spectral unmixing algorithm in the Spectral Image Processing System (SIPS) software (CSES, 1992a) because (1) we were familiar with the use of this method and because of the ease of use of the software, and (2) we knew mixtures exist in the study area, such as rock-plus-vegetation near timberline and mixed talus on the lower slopes around Eagle Ridge. One advantage of the unmixing technique is that it can map pixels that match endmembers, as well as pixels that are mixtures of endmembers, and, therefore, can function as both a spectral matching and unmixing algorithm. The result of the unmixing is an image (map) for each endmember that represents the fractional abundance of that endmember in each pixel (CSES, 1992a).

Endmember Selection

Endmembers were selected based on our knowledge of the geology in the study area and on laboratory spectral measurements of field samples. We extracted endmember spectra from the calibrated AVIRIS image in areas that are well exposed and spectrally distinct. These spectra are averages of at least 20 pixels.

Initially, four endmembers were selected, one each from the three units most evident in an AVIRIS color-composite image (the Ottertail Formation, and two units in the McKay Group), plus one endmember of vegetation from a forested area in the valley. The root-mean-square (RMS) error image from the initial unmixing showed a number of unmapped or poorly mapped areas, which indicated that the materials in these areas were not well characterized by the initial set of endmembers. The most prominent unmapped areas turned out to be snow, spectrally bright vegetation adjacent to drainage channels, and a circular area in the middle of the area mapped as McKay. We added endmembers to represent these materials, as well as an endmember from the spectrally flat alkaline rock units. In addition, a carbonatite endmember was added to differentiate the carbonatite plug from carbonate-bearing country rocks. This carbonatite endmember was not originally included because, as noted above, the carbonatite plug was almost completely covered by grass and trees or was in shadow, and we supposed, therefore, that it would not be spectrally distinct. However, closer examination of the spectra from pixels within the plug did reveal eight to ten pixels that had no vegetation influence and a moderately intense CO_3 absorption feature. These pixels were averaged and then added to the endmember list. The subsequent unmixing run mapped the carbonatite endmember in the McKay in the southern part of the study area, which, although incorrect, is consistent with the carbonate composition of these country rocks. In an attempt to differentiate between carbonate of the southern McKay and carbonate of the carbonatite plug, we selected an additional McKay endmember from a vegetation-free area in the south.

This iterative process resulted in ten endmembers that yielded the most complete mapping of the study area and provided the best separability among mineralogic and lithologic units. They include seven mineralogic (Figure 4) and two vegetation endmembers and one snow endmember. Table 1 summarizes the spectral and compositional characteristics of the seven mineralogic endmembers. The spectral differences among the four McKay endmembers result from
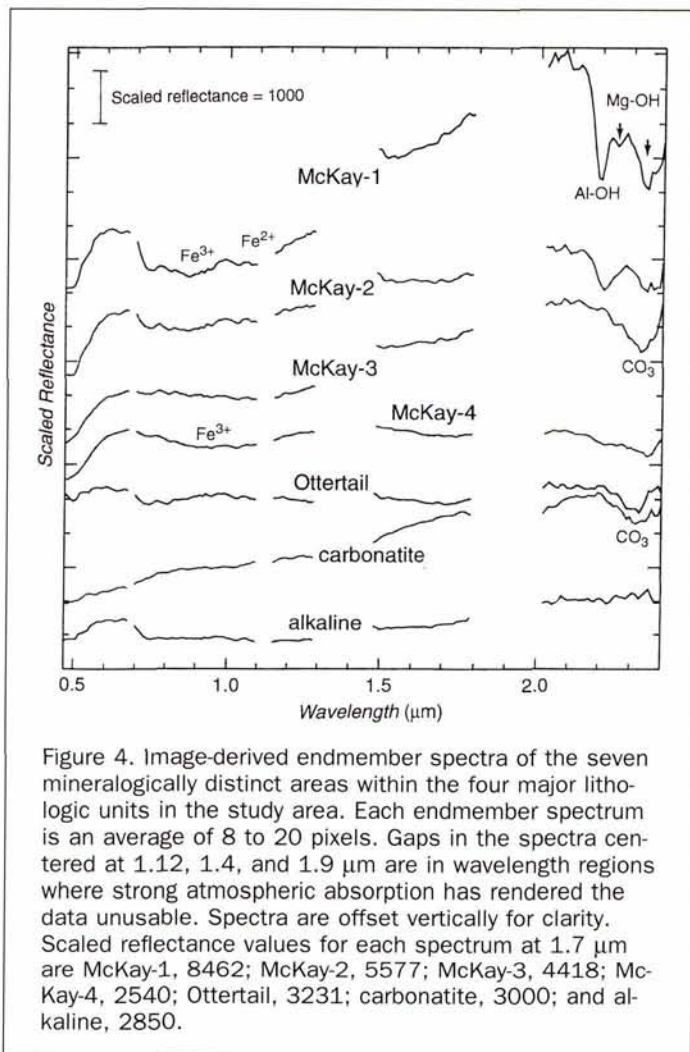
Figure 4. Image-derived endmember spectra of the seven mineralogically distinct areas within the four major lithologic units in the study area. Each endmember spectrum is an average of 8 to 20 pixels. Gaps in the spectra centered at 1.12, 1.4, and 1.9 µm are in wavelength regions where strong atmospheric absorption has rendered the data unusable. Spectra are offset vertically for clarity. Scaled reflectance values for each spectrum at 1.7 µm are McKay-1, 8462; McKay-2, 5577; McKay-3, 4418; McKay-4, 2540; Ottertail, 3231; carbonatite, 3000; and alkaline, 2850.

various combinations and abundances of goethite, chlorite, muscovite, and calcite. The Ottertail endmember has a broad carbonate feature and a relatively flat spectrum with a shallow feature centered at 0.78 µm. The alkaline-rock endmember spectrum has a reflectance maximum at 0.65 µm but contains no obvious absorption features between 0.7 µm and 2.4 µm.

Results

Plate 1 shows a composite image of all seven endmember maps with a 3 by 3 spatial mode filter applied and the digitized published geology from Figure 1 superimposed. Each color shows the distribution of pixels with a high fractional abundance of a particular endmember. The individual maps have been superimposed such that, in the few rare cases where two image endmembers had high abundance within the same area, the endmember that we interpreted to most closely match the image spectra in that area overlays the other.

The McKay-1 endmember is displayed in blue and corresponds to the best exposed and brightest areas in the north. The McKay-2 endmember (pink) occurs in the circular area in the center of the area mapped by Currie (1975) as McKay and in two patches that extend to the southeast. The McKay-3 endmember (green) was mapped in the southern part of the study area in vegetation-free patches on the eastern slopes of Eagle Ridge. The McKay-4 endmember (red) was mapped

best on south-facing slopes in the center of the image along the contact with the Ottertail Formation. Two of the endmembers (McKay-2 and -4) also were mapped in several small patches along a linear trend on the western slopes of Eagle Ridge in the north (A).

The Ottertail endmember was mapped along the crest of Eagle Ridge and downslope to the northwest (cyan, Plate 1). Other coherent areas of cyan pixels were mapped on the eastern slopes of Eagle Ridge (B and C; Plate 1) where Ottertail talus masks the underlying bedrock.

The largest area mapped as alkaline rocks (magenta, Plate 1) is in well-exposed rocks on the crest and eastern slopes of Eagle Ridge at the northern edge of the image. The thin arm extending southwest from the large area is a drainage that contains alkaline rock talus from outcrops higher on the ridge. Other smaller areas are confined to the middle of the eastern slopes of Eagle Ridge and in outcrops exposed along drainages extending down through the trees (D; Plate 1).

A very noticeable patch (E) that mapped as carbonatite (yellow, Plate 1) is on a short ridge extending eastward from Eagle Ridge, corresponding to the area mapped by Currie (1975) as a carbonatite plug. Two smaller patches (F; Plate 1) occur in drainages extending from Eagle Ridge. The large areas that mapped as the carbonatite endmember to the south along Eagle Ridge are not carbonatite, but rather are exposures of McKay Group rocks with some vegetation cover. So, instead of unmixing as McKay-3-plus-vegetation, apparently, a carbonatite-plus-vegetation mixture better reproduces the observed AVIRIS spectra in this area. A plausible reason for this is that, in mixtures with vegetation, the differences between the McKay-3 and carbonatite endmembers are insufficient to allow accurate unmixing. To test this, we performed the unmixing omitting the carbonatite endmember. All pixels that mapped as carbonatite in the first unmixing mapped as McKay-3 in the second unmixing. Therefore, our attempt to distinguish between carbonate of the carbonatite and carbonate of the southern McKay Group was only partially successful. This is not necessarily a limitation of the unmixing algorithm and might be resolved with higher signal-to-noise data, or by improved calibration procedures. It can be noted, however, that, although the specific endmember chosen was incorrect, the results are consistent with the carbonate mineralogy of the McKay Group in this area.

Discussion and Conclusions

Our image-map shows close agreement with the published geologic map in areas above timberline. Our map also reveals structural information in general agreement with that of the

TABLE 1. SPECTRAL FEATURES AND MINERAL BAND ASSIGNMENTS OF THE SEVEN MINERALOGIC ENDMEMBERS IN FIGURE 4. (M) DENOTES MINERAL IS PRESENT IN MINOR AMOUNTS.

| Endmember	Spectral Feature and Position (µm)	Mineralogy	Color in Plate 1
McKay-1	Al-OH (2.19)	muscovite	blue
	Mg-OH (2.25, 2.34)	chlorite	
	Fe^{2+} (1.1), Fe^{3+} (0.87)	chlorite	
McKay-2	Al-OH (2.20)	muscovite (m)	pink
	Mg-OH (2.35)	chlorite (m)	
	Fe^{3+} (0.87)	chlorite (m)	
McKay-3	CO_3 (2.33)	calcite	green
	Fe^{3+} (0.8-1.2)	goethite (m)	
McKay-4	Fe^{3+} (0.95)	goethite	red
	Mg-OH (2.35)	chlorite (m)	
Ottertail	CO_3 (2.33)	calcite	cyan
Alkaline	NONE	nepheline, augite	magenta
Carbonatite	CO_3 (2.31)	dolomite	yellow
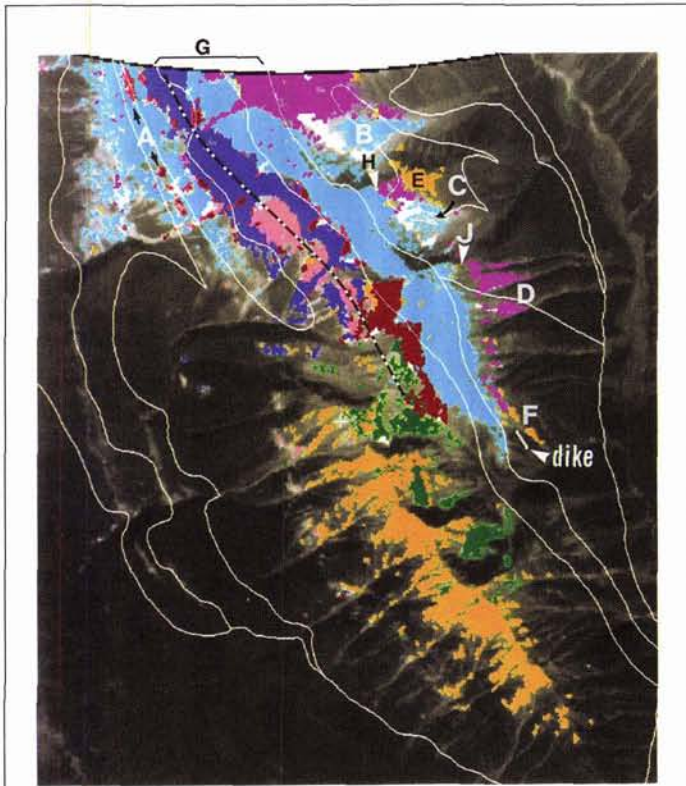
Plate 1. Composite of the seven endmember maps: Mc-Kay-1, blue; McKay-2, pink; McKay-3, green; McKay-4, red; carbonatite, yellow; Ottertail, cyan; alkaline rocks, magenta. The digitized geologic map generalized from Currie (1975) is superimposed in white. The dashed line is our trace of a synclinal axis. For reference, the above are overlain on a grey-scale image of AVIRIS band 28. Almost all of the unmapped area is below timberline and completely covered with vegetation, or in shadow (darkest patches along Eagle Ridge), or covered with snow (white patches on the eastern slopes of Eagle Ridge). Speckle has been reduced and mapped areas made a little more coherent by the application of a 3 by 3 box mode filter.

the Ice River is very difficult because of the rugged terrain. Contacts can only be approximated in inaccessible areas that cannot be traversed. This problem became apparent when the AVIRIS image maps and the geologic map were compared in detail. We found two significant discrepancies between the image map and the published geologic map. One occurs in the northwestern extension of the Ottertail Formation and McKay Group near the top of the image (G; Plate 1). The published lithologic contacts deviate substantially from the AVIRIS-derived contacts. We confirmed the accuracy of the AVIRIS maps by examining both AVIRIS color-composite imagery and aerial photographs. Both clearly show the alkaline rock-Ottertail Formation contact crossing over the ridge and continuing down the western slope of Eagle Ridge, instead of following the ridge as indicated on the published map.

Second, note the clearly visible zigzag pattern of the Mc-Kay-4 endmember (red in Plate 1). This pattern delineates a limonitic unit at the base of the McKay group along the contact with the Ottertail Formation. The zigzag contact is the result of the westward dip of the unit on the dissected western slopes of Eagle Ridge. Note, however, the omission of the zigzag contact on the geologic map.

Several other differences are illustrated in Plate 1 (F, H, and J). At F, our image map shows a narrow, dike-like outcrop of rock which was mapped as the carbonatite endmember. However, the nearest mapped carbonate-bearing rock is the carbonatite dike positioned up slope. There is undoubtedly carbonate-bearing rock exposed in this area; but, we have yet to confirm the exact relationship between the AVIRIS mapped "dike" and the dike on the published map. At H and J, our image map shows distinct contacts between units in areas of outcrop, yet they do not coincide with the contacts on the geologic map. These discrepancies are not the result of poor image-to-map registration. We carefully examined the registration and found that distinct topographic features in the image, such as peaks and the crest of Eagle Ridge, closely align with the same features digitized from the topographic maps of the area (see Figure 2).

This study thus illustrates the value of imaging spectrometer data as an aid to lithologic mapping. Both mineralogic and lithologic differences, as well as structural trends, can be interpreted from these data. We show how, from just a few field samples, along with visual and spectral examination of high spectral-resolution imagery, large-scale reconnaissance mapping can be done successfully.

Acknowledgments

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published map. The published geologic map shows a synclinal axis (not shown in Plate 1) along the northwest extension of the McKay Group. The dashed line on the image-map represents our placement of the synclinal axis as indicated by the repetitive pattern of the Ottertail Formation and McKay Group, and by the northwest-converging pattern of the Mc-Kay-1 endmember map (blue).

Our map contains additional information regarding the lateral and vertical mineralogic differences within the McKay Group. Our mapping indicates that spectrally the McKay Group is carbonate-dominated in the south, whereas, in the north, muscovite and chlorite are in sufficient quantity to dominate the spectral signatures of two of the three endmembers mapped there. The vertical succession of endmembers in the north, from bottom to top, as revealed by the repetitive pattern is McKay-4, McKay-1, McKay-2, which indicates a vertical increase then decrease of muscovite and chlorite. Although not addressed in this study, this ability to map mineralogic variations has potential utility in mapping sedimentary and metamorphic facies.

In addition, traditional field mapping in an area such as

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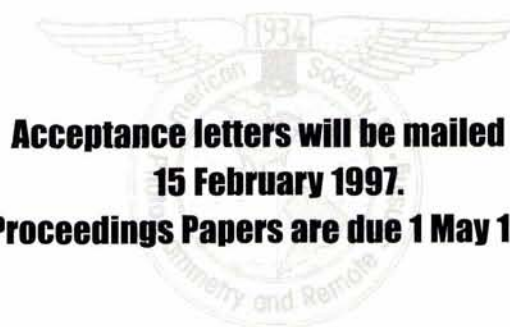*Send abstracts to:*
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