AIRBORNE IMAGING SCANNER SURVEY OF NORTHEASTERN MINNESOTA

by

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ABSTRACT

An airborne imaging scanner survey was flown over two areas in the Duluth Complex and one area along the Vermilion fault zone on September 12, 1988 to detect heavy metal induced stress in plants due to the presence of buried mineral deposits. The Duluth Complex flight lines covered copper-nickel and iron-titanium mineral deposits while the Vermilion fault flight line covered Archean gold mineralization sites. The 63 channel imaging scanner had a spatial resolution of about 9-10 meters and a flight path width of approximately 6.4-7.2 kilometers along three flight lines.

Supervised, unsupervised, principal components and inverted principal components analysis and Chebyshev polynomial expansions were used on data collected over two test sites, i.e., the east end of the Archean flight line and the Dunka Pit area, to learn whether or not vegetative stress could be identified in areas with known metallic mineralization. Interpretation of the Dunka Pit test site was abandoned because: 1) the test site was too small; 2) much of the canopy was dead; and 3) the test site was overwhelmed by an adjacent, highly reflective mine dump. At the Archean site, ground spectroradiometer data was collected to assist with the interpretation of the imaging scanner data. The ground data indicated spectral shifts to both longer and shorter wavelengths in vegetation over mineralized compared with unmineralized sites. However, the imaging scanner data did not indicate any evidence of vegetative stress in mineralized areas. At this point, the imaging scanner survey data are useful mainly for discriminating different types of vegetation.

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INTRODUCTION

An airborne or ground spectrometry survey can be used to detect buried or hidden mineral deposits by identifying stressed vegetation over mineralized areas. Heavy metals in the soil or bedrock can be absorbed by plant roots if they are accessible and chemically available. Anomalously high concentrations of heavy metals can induce stress in the plant. This vegetative stress might then be detected by an airborne or ground spectrometer and interpreted through a comparison of spectral patterns of similar species on and off mineralized sites. Generally, there is an apparent shift in the spectral signature of the plant species to shorter wavelengths when the plant is under stress. It is likely that this apparent shift actually reflects an inhibition of the maturation process that normally leads to an increase in chlorophyll and concurrent deepening of the chlorophyll absorption band (Milton, *et al*, in prog.).

We tested these hypotheses by comparing both airborne and ground spectral signatures of plant communities in mineralized and unmineralized areas. Mineralized areas tested included both Cu-Ni occurrences in the Duluth Complex and gold-related elements in the Archean greenstones. The plant communities were all members of the Great Lakes mixed boreal-hardwood biome.

AIRBORNE IMAGING SCANNER SURVEY

The airborne imaging scanner survey was flown on September 12, 1988, over a portion of the Archean Vermilion greenstone belt and the northwestern edge of the Duluth Complex (Fig. 1; Table 1). These two areas were selected by a joint NRRI-

USGS-MDNR committee based upon gold exploration activity in the Vermilion greenstone belt and known occurrences of copper-nickel and iron-titanium mineral deposits at or near the surface along the northwestern edge of the Duluth Complex. The committee also compiled a preliminary target list of areas with known metallic mineralization in northern Minnesota (Table 2). In addition, two of these sites/areas were to be selected for interpretation of the airborne data.

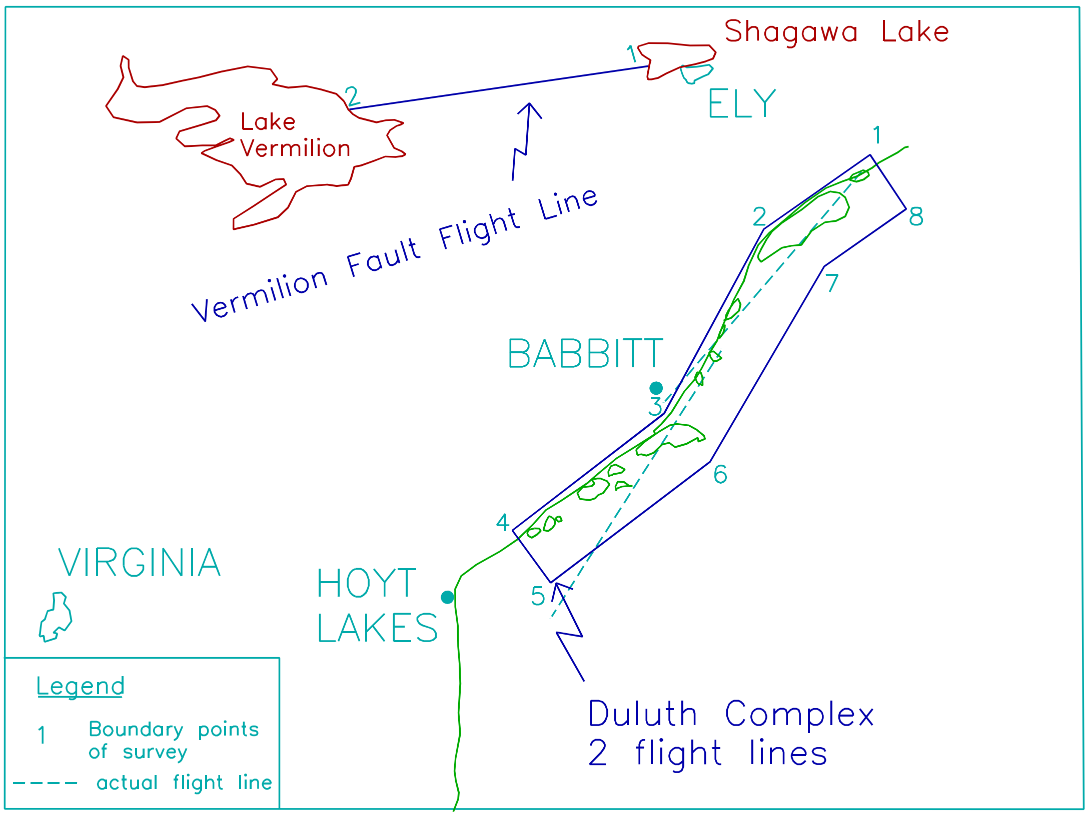

Figure 1. Location of airborne imaging scanner survey flight lines.

Site priority was based upon the availability of "ground truth" data, e.g., vegetation data, known metallic mineralization, soil and stream sediment surveys, etc. These data were collected to help define areas that had potentially stressed vegetation. However, data were only collected on the four highest priority sites due to budget restrictions (Table 2). Data on the Dunka Pit and the 1st Archean sites and Minnamax sites were input into Lotus spreadsheets (Appendix D). These "ground truth" data were, where possible, referenced to the UTM coordinate system. Ground truth data for the Spruce Road site can be found in Agrawal (1964), Alminas (1975) and Meineke, *et al* (1977).

Table 1A. Proposed Geographic Limits for the Airborne Imaging Scanner Survey - Duluth Complex Flight Lines

1. Bogberry Lake 7 1/2 minute quadrangle
   Longitude - 91E40'40" W
   Latitude - 47E50'41" N
   T. 62 N., R. 11 W., Section 24, NW 1/4, NW 1/4, SE 1/4

2. Kangas Bay 7 1/2 minute quadrangle
   Longitude - 91E47'2" W
   Latitude - 47E47'46" N
   T. 61 N., R. 11 W., Section 6, SE 1/4, NW 1/4

3. Babbitt 7 1/2 minute quadrangle
   Longitude - 91E53'48" W
   Latitude - 47E39'22" N
   T. 60 N., R. 12 W., Section 29, NW 1/4, NE 1/4

4. Allen 7 1/2 minute quadrangle
   Longitude - 92E3'52" W
   Latitude - 47E34'49" N
   T. 59 N., R. 14 W., Section 24, NW 1/4, SE 1/4, SE 1/4

5. Allen 7 1/2 minute quadrangle
   Longitude - 92E1'36" W
   Latitude - 47E32'48" N
   T. 59 N., R. 13 W., Section 32, SW 1/4, NW 1/4, SE 1/4

6. Babbitt NE 7 1/2 minute quadrangle
   Longitude - 91E51'9" W
   Latitude - 47E37'50" N
   T. 60 N., R. 12 W., Section 34, SW 1/4, SW 1/4, SE 1/4

7. Bogberry Lake 7 1/2 minute quadrangle
   Longitude - 91E43'20" W
   Latitude - 47E46'3" N
   T. 61 N., R. 11 W., Section 15, SW 1/4, NW 1/4, SE 1/4

8. Bogberry Lake 7 1/2 minute quadrangle
Longitude - 91E37'56" W
Latitude - 47E48'56" N
T. 62 N., R. 10 W., Section 32, NW 1/4, SE 1/4, NW 1/4

Table 1B. Proposed Geographic Limits for the Airborne Imaging Scanner Survey - Vermilion Fault Flight Line

1. Shagawa Lake 7 1/2 minute quadrangle
Longitude - 91E54'17" W
Latitude - 47E54'37" N
T. 63 N., R. 12 W., Section 30, SE 1/4, NE 1/4, NE 1/4

2. Chad Lake 7 1/2 minute quadrangle
Longitude - 92E 14'16" W
Latitude - 47E52'49" N
T. 62 N., R. 15 W., Section 3, NW 1/4, SE 1/4, SW 1/4

Table 2. Priority List of Mineralized Sites for Airborne Imaging Scanner Interpretation

1. Dunka Pit
2. 1st Archean gold sites - Raspberry Prospect
3. Spruce Road copper-nickel deposit
4. Minnamax (Babbitt) copper-nickel deposit
5. 2nd Archean gold site
6. Section 17 Fe-Ti deposit
7. South Filson Creek Cu-Ni-Ag-PGE deposit
8. Dunka Road copper-nickel deposit
9. 3rd Archean gold site
10. MDNR vegetation control plots
11. Wetlegs copper-nickel deposit
12. Serpentine copper-nickel deposit
13. Longear/Longnose Fe-Ti deposits

The airborne survey was flown by Geophysical Environmental Research Corporation of New York, New York, using a 63-channel airborne imaging scanner. The imaging scanner was flown with 31 evenly spaced channels of 15.4 nanometer (nm) width from 450 nm to 900 nm, 4 broad channels between 900 and 2000 nm, and 28 channels 16.2 nm wide from 2000 to 2500 nm. Spatial resolution was approximately 10 meters (Table 3).

Table 3. Geographic Endpoints and Spatial Resolution of the Airborne Imaging Scanner

Flight line 1: Southwest of Dunka Pit

NE endpoint: 47E39'45" 91E52'00" - Babbitt NE quad.
SW endpoint: 47E30'15" 92E02'30" - Allen quad.

Flight path width: approx. 7.2 km (approx. 4.5 mi.)
Spatial resolution: approx. 10 meters
Flight line length: approx. 20.4 kms (12.7 mi.)

Flight line 2: Dunka Pit area to Spruce Road

NE endpoint: 47E51'30" 91E39'20" - Bogberry Lake quad.
SW endpoint: 47E39'30" 91E53'15" - Babbitt quad.

Flight path width: approx. 7.2 km (approx. 4.5 mi.)
Spatial resolution: approx. 10 meters
Flight line length: approx. 27.2 km (16.9 mi.)

Flight line 3: Vermilion Fault

East endpoint: 47E55'00" 91E53'00" - Shagawa Lake quad.
West endpoint: 47E51'15" 92E09'00" - Chad Lake quad.

Flight path width: approx. 6.4 km (approx. 4 mi.)
Spatial resolution: approx. 9 meters
Flight line length: approx. 24.8 km (15.4 mi.)

The airborne survey was flown approximately 5-10 days after the leaves began to change color. Approximately 1% of the vegetation in the survey areas had begun to change color. Since there had been no frost in the survey area, the beginning of senescence may have been initiated by the drought of the preceding two years, reflecting the effects of water stress on the vegetation.

The new imaging scanner flown for this survey had not previously been used for studies of metal-induced stress effects in northern boreal forest vegetation. Therefore, some ground spectroradiometry data and vegetation distribution data were collected to assist with the interpretation of the airborne scanner survey data (Appendix A). These data were collected as a part of a LCMR sponsored biogeochemistry project.

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Funding for this study was made available by a grant from the Minerals Coordinating Committee through the Minerals Diversification Plan, which is gratefully acknowledged. Additional funding for this project was provided by the Legislative Commission on Minnesota Resources as a part of a biogeochemical prospecting project to study the biogeochemistry and ground spectral reflectance signatures of plant species in areas with known metallic mineralization. Funding for this project is also gratefully acknowledged. Property access was provided by Mr. Roger Kuhns of BHP-Utah International, Mr. Keith Laskowski of Newmont Exploration, Mr. Steve Mornis of American Copper & Nickel, Inc., Mr. William Ulland of American Shield Corporation, and LTV Steel, which are also gratefully acknowledged.

GEOLOGY OF NORTHERN MINNESOTA

The geology of northeastern Minnesota consists of three distinct geologic terrains; Archean greenstone belts, Lower Proterozoic sediments, with banded iron-formation and the Duluth Complex and related North Shore Volcanic Group. The airborne imaging scanner survey covers a portion of the Archean Vermilion greenstone belt and the northwestern edge of the Duluth Complex (Fig. 1; Table 3).

ARCHEAN GREENSTONE BELTS

The Archean (2.7 Ga) granite-greenstone terrains in northern Minnesota form the southern part of the Superior Province of the Canadian Shield. The Vermilion greenstone terrane consists of dominantly mafic tholeiitic rocks with minor metasedimentary and felsic volcanic and volcaniclastic rocks. The sedimentary sequence consists of lenses of banded iron-formation and volcaniclastic graywacke-shale sequences (Morey and Van Schmus, 1988). Synvolcanic felsic intrusions intrude the entire volcanic-sedimentary sequence.

The Vermilion fault is an east-west striking curvilinear fault with many subsidiary faults (Sims, 1972). Much of the gold exploration in the Vermilion greenstone belts is concentrated around the Vermilion fault and its subsidiary faults (Southwick, 1989).

DULUTH COMPLEX

The Duluth Complex consists dominantly of mafic igneous rocks (troctolite and gabbro) of Keweenawan age (1.1 Ga). These rocks are exposed in an arcuate

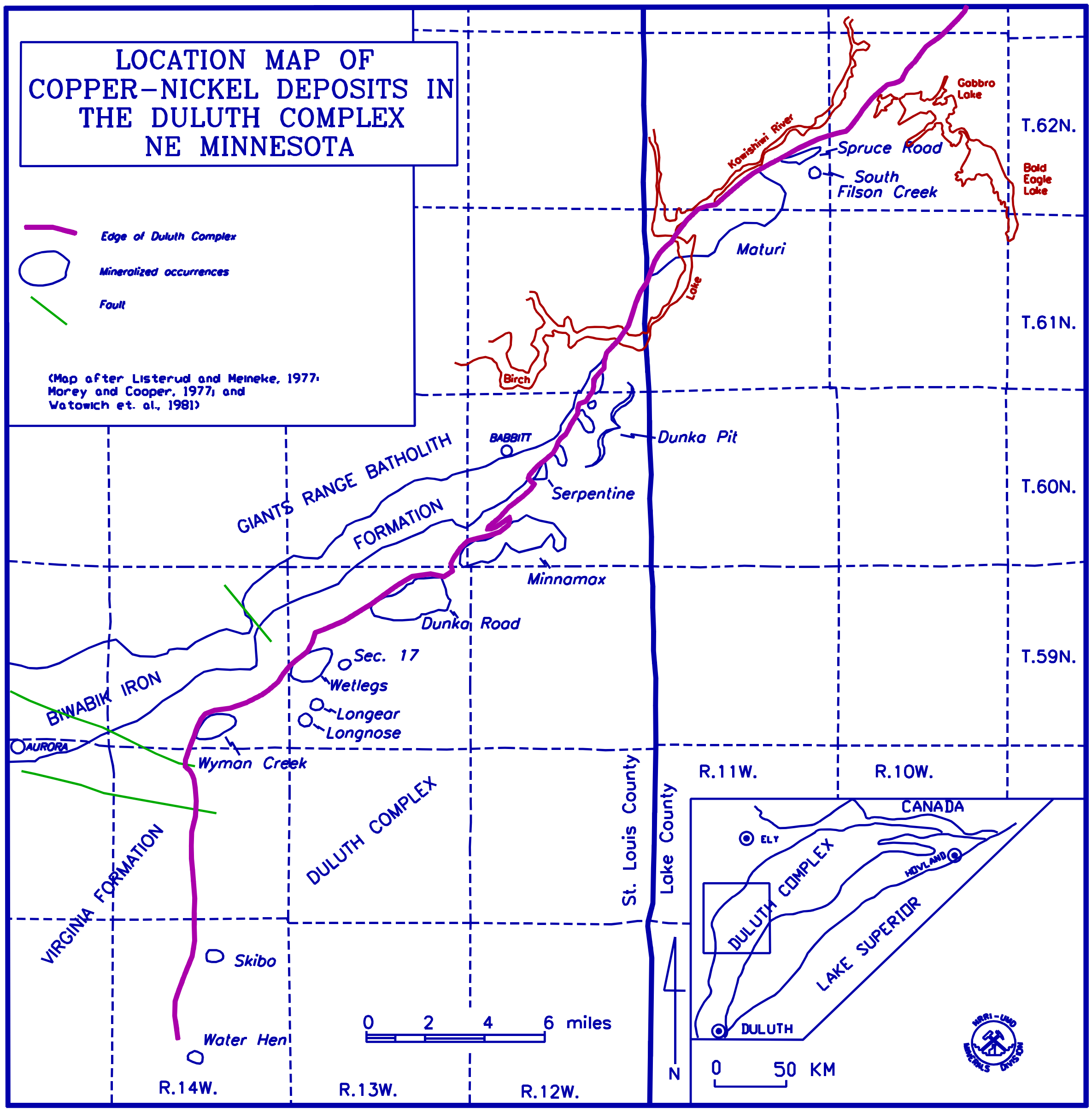

Figure 2. Location map of mineral occurrences in the Duluth Complex.

body extending from Duluth, north toward Ely and then east to Hovland (Fig. 2). In general, the Duluth Complex rocks are subdivided into an older anorthositic series (Davidson, 1972) and a younger troctolitic series (Bonnichsen, 1972). The troctolitic series is subdivided into several informal intrusive bodies, e.g., Partridge River intrusion (PRI), South Kawishiwi intrusion (SKI), Bald Eagle intrusion, etc. (Foose and Weiblen, 1986). The PRI is still further subdivided into several stratigraphically continuous igneous units (Severson, 1988; Severson and Hauck, 1990).

Six different types of mineralization occur in the Duluth Complex: 1) Cu-Ni sulfides along the basal contact zone with the footwall rocks and as "cloud zone" sulfides above the basal mineralization; 2) platiniferous, chromium-rich, olivine-plagioclase cumulates; 3) hydrothermal Pd-Pt-Au-Cu mineralization associated with late-stage faulting; 4) Ti-Fe-V mineralization associated with Oxide-bearing Ultramafic Intrusions (OUI); 5) Ti-Cu-Ni mineralization that is mixed Ti-Fe-V and basal Cu-Ni sulfide mineralization. This mineralization is constrained by the geology and petrogenesis of the host rocks (Severson, 1988, Severson and Hauck, 1990) and by late-stage tectonics (Hauck and Barnes, 1989); and 6) titaniferous magnetites associated with the anorthositic series rocks. All but the last type of mineralization (#6) are covered by the airborne imaging scanner survey (Figs. 1 and 2). However, the platiniferous, chromium-rich, olivine cumulates occur at a depth of about 2,500 ft. in a drill hole northeast of the Dunka Pit (Fig. 1) and are not, at this time, known to crop out or subcrop beneath the glacial overburden. However, Buchheit, *et al*, (1989) and Morton and Reichhoff (1989) have shown that chromium-rich spinels similar to spinels with the deep platinum mineralization do occur in the flight line area and also further to the east of the flight line. The OUIs (#4) occur north of point 5 on Figure 1.

ECOLOGY OF NORTHERN MINNESOTA

REGIONAL VEGETATION ECOLOGY

The western Lake Superior region is at the boundary between the boreal forest to the north and the northern hardwoods to the south and east. Tree species include such typically boreal conifers as white and black spruce (*Picea glauca*, *P. mariana*) and balsam fir (*Abies balsamea*) and northern hardwoods such as red and sugar maple (*Acer rubrum, A. saccharum*), basswood (*Tilia americana*), and yellow birch (*Betula allegheniensis*). Aspen (*Populus tremuloides*, *P. grandidentata*) and paper birch (*Betula papyrifera*) are early successional species common to both northern hardwoods and boreal conifers (Pastor and Mladenoff, 1990). White and red pines (*Pinus strobus*, *P. resinosa*) are common dominants of both biomes and are often the largest trees in any forest in the region.

Rowe (1972) classifies the forest of this region as Great Lakes St. Lawrence Mixed Conifer-Hardwood. However, the mix of species of both boreal and northern hardwood biomass is not homogeneous across the region or across the landscape at any one point in the region (Brown and Curtis, 1952; Maycock and Curtis, 1960; Pastor and Mladenoff, 1990). Northern hardwoods are predominant in the Upper Peninsula of Michigan, where boreal conifers are confined to bogs. Moving northwestward to Minnesota and the Boundary Waters region, the climate becomes colder and drier, allowing boreal conifers to creep out onto the upland and displace northern hardwoods. In northern Minnesota, the vegetation is predominantly early successional aspen and paper birch with understory to co-dominant strata of boreal conifers and towering dominant white and red pines remnant from logging around the turn of the century. Maples are usually confined to warmer slopes, particularly when these slopes are also covered with clay-rich glacial drift that retains adequate water for these drought sensitive species (Kittredge, 1938; Maycock and Curtis, 1960). On rockier sites there is a strong component of pines (Heinselman, 1973). Bogs and wetlands are almost uniformly occupied by black spruce and tamarack (*Larix laricina*). Fire is also an important factor determining the distribution of species in the area (Heinselman, 1973; Swain, 1980; Grigal and Ohmann, 1975; Clark, 1988; Baker, 1989). Jack pine (*Pinus banksiana*), aspen, and spruce are common early successional species after fires, but the exact successional pathway depends on seed availability, fire size, and fire intensity.

Nitrogen is the soil nutrient most limiting to plant growth in boreal forests (Weetman, 1968; Stewart and Swan, 1970; Krause, 1981; Van Cleve and Oliver, 1982; Pastor *et al*, 1987). At the same time, the different tree species affect soil nitrogen availability through the decomposition of their leaf litters. Conifer leaf litter generally depresses nitrogen availability while that of hardwoods increases it (Flanagan and Van Cleve, 1983; Pastor, *et al*, 1987, Pastor and Mladenoff, 1990). To our knowledge, no one has investigated the relationships between tree growth and heavy metals in soils of the region. Heavy metals could affect tree growth and species composition directly by differentially stressing different species and/or indirectly by affecting the microbial community responsible for converting nitrogen from organic to plant available, inorganic forms. If boreal conifers accumulate heavy metals in their leaf litter (Dunn, 1980), then the microbial community may be stressed. This may further stress plant growth if nitrogen availability is in turn reduced. Both direct heavy metal stresses on trees and indirect stresses through reduced nitrogen availability would be expressed as leaf chlorosis and spectral anomalies in canopy reflectance.

To test these hypotheses, two mineralized test sites within the survey area were selected. The first, Site A, was a Duluth Complex site having known Cu-Ni mineralization. The second, Site B, was an Archean greenstone site having known gold-related mineralization.

<u>SITE A ECOLOGY</u>

Site A (Fig. 3) is located in a peat-filled valley that is dissected by a small creek. The peat is well-decomposed and is of variable depth. A seep, emanating from gabbro stockpiles in the adjacent uplands, flows through the site and drains into the creek.

The vegetation in the cedar bog is dominated by white cedar (*Thuja occidentalis*) of varying size

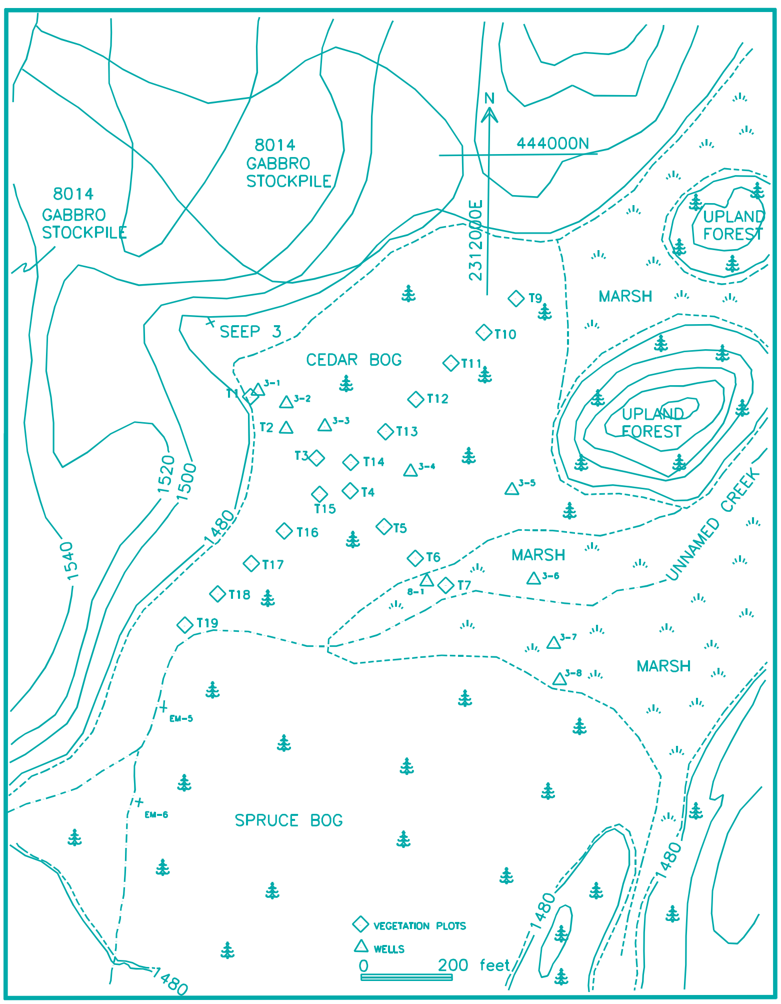

Figure 3. Botanical and geographic map of the Seep 3 area, Dunka Pit, St. Louis County.

and density. The densest cedar forms a band oriented parallel to the upland border. Sub-canopy trees scattered throughout the white cedar include balsam fir (*Abies balsamea*) and black spruce (*Picea mariana*). Green alder (*Alnus rugosa*) and sedges (*Carex spp.*) make up the understory. Scattered hummocks of

sphagnum moss (*Sphagnum spp.*) and pools of standing water also are present. Towards the interior of the peatland, the cedar bog/swamp grades into a marsh dominated by sedges (*Carex stricta*) and scattered shrubs (*Salix spp.*). A small area near the seep is devoid of trees and is dominated by horsetails (*Equisetum spp.*) and cattails (*Typha latifolia*).

The site is bordered by forested mineral islands and black spruce swamp (Fig. 3). The mineral islands are dominated by quaking aspen (*Populus tremuloides*) and white spruce (*Picea glauca*). The black spruce bog/swamp is dominated by black spruce and has an understory of ericaceous shrubs, e.g., leatherleaf (*Chamaedaphne calyculata*) and sphagnum moss.

SITE B ECOLOGY

The terrain is moderately rugged at this site, with alternating topography, e.g. lowland/upland/lowland/upland, from north to south across the property. The transition can be either abrupt or gradual. The glacial cover is generally thin, varying from exposed bedrock in many upland and transition locations to a probable maximum depth of 25 feet in lowland areas.

Historically, the site has experienced mineral exploration and logging activity off and on for most of this century. Coupled with the varying topography of the area, this has resulted in a mixed suite of vegetation with a moderately open canopy.

Upland and Transition Species

The upland and transition areas have the widest diversity of species, with a mixture of coniferous and deciduous types. The soils tend to range from dry to moist (but not wet or saturated) and are well drained.

Populus tremuloides (Quaking aspen)

> Deciduous. The most common deciduous species, varying in size from saplings in recently logged areas to mature trees. Prefers well-drained soils.

Betula papyrifera (Paper birch)

> Deciduous. The second most common deciduous species, frequently associated with the aspen. Seems to prefer southern slopes; best stands are located on the southwest part of the property.

Pinus resinosa (Red pine; a.k.a. Norway pine)

> Conifer. Restricted to areas where soil is thin; usually dry ridges where bedrock is exposed. Tallest trees on property.

Populus grandidentata (Large-tooth aspen)

> Deciduous. Present, but much more limited in extent than quaking aspen. When present, occurs in small stands on north-facing slopes on transitional to upland exposures.

Abies balsamea (Balsam fir)

> Conifer. Ubiquitous; but generally sub-canopy.

Acer spicatum (Mountain maple)

> Deciduous. Ubiquitous; more shrub-like than tree-like, based on its common size (5 to 10 feet). Dense in areas having ample sunlight.

Corylus cornuta (Beaked hazelnut)

Deciduous. The most common shrub species. Prefers well-drained, drier soils.

Picea glauca (White spruce)

Conifer. Present but less common than balsam fir. Occurs in small stands on north-facing slopes or in the understory beneath aspen.

Lowland Species

Two different lowland environments occur at this site; the first dominated by dense cedar stands and the second by more open-canopy black ash stands. Saturated soils are present in both environments.

Thuja occidentalis (Northern white cedar)

Conifer. Major stands occur at the northern and southernmost extent of the property. However, scattered individuals are present in some transitional to upland locations.

Fraxinus nigra (Black ash)

Deciduous. The major stands occur largely in low, flat, cool, and moist areas between transitional to upland areas.

Alnus rugosa (Speckled alder)

Deciduous. Scattered and restricted to damp locations. Tends to be present where *Corylus cornuta* is absent.

Picea mariana (Black spruce)

Conifer. Much less common than cedar at this site. When present, occurs in monotypic stands, usually with sphagnum moss ground cover. Indicates less fertile soil than cedar.

AIRBORNE IMAGING SCANNER SURVEY

IMAGE PROCESSING TECHNIQUES

The following discussion relates to standard image processing techniques and products for imaging scanner data, in alphabetical rather than logical order.

Classifications - Multispectral classification is a way to class or categorize pixels (picture elements) by their spectral signatures. **Supervised classifications** are done using training sites about which much is known. **Unsupervised classifications** use no prior knowledge of the field sites, but group areas having similar spectral patterns.

Color-infrared (CIR) - CIR is composed of two visible and one infrared channels, each assigned a separate color (blue, green, red). This is a standard first-step image on which subsequent processing is based. This image is good for separating broad cover types (coniferous forest from deciduous forest from open marsh).

Color-ratio composites (CRC) - Ratio images emphasize reflectance variations, and thus enhance our ability to identify differences in spectral reflectance between two or more materials, cover types, etc. A number of ratios are tested based on knowledge of the field area before those that are best for a particular situation are chosen and combined in one or more image products.

Principal components (PC) - The principal components transformation fits a new set of coordinate axes to the image data to compress the variance in a multispectral data set. This reduces the redundancy that results from high band-to-band correlation. As a result, image noise decreases, spectral differences between materials become more apparent, and all the scene variance is displayed in one or two images. As with ratios, three PC images are combined to make a color image. Several combinations may be tested before the optimum PC image is created.

Inverted principal components (IPC) - The inversion process returns the new PC coordinate system to the wavelength axis, so that the colors present in the image more accurately relate to the original channel input. That is, the now compressed data, minus noise and redundancy, are put back into a wavelength context, so that an area of red relates to the original data input from the red channel. PC images are difficult to interpret because their colors look strange and out of context. The IPC image facilitates interpretation of the PC data by returning to the original coordinate system.

Chebyshev polynomial expansion/ratios - In the opinion of Collins, *et al* (1983), a frequency domain analysis is the most sensitive method for measuring metal-induced spectral changes in the field. Frequency information is usually extracted from spectral measurements using the change in radiance relative to a change in wavelength (dI/dlambda). However, for very narrow-band systems such as GER's old 256-channel airborne spectroradiometer, there are the problems of atmospheric absorption bands and Fraunhofer lines (variations in solar flux as it reaches earth).

To account for these features' interference with extraction of frequency information, Collins, *et al* (1983) use a waveform analysis technique to transform the spectral function into a polynomial expansion series that approximates the natural data. The Chebyshev polynomial method is sensitive to the lower-frequency information needed for minerals exploration in vegetated areas, while filtering out the higher frequency atmospheric and solar features. However, this type of analysis is best suited to very narrow-band spectral work, and not as well to the image data provided by the airborne imaging scanner. As GER suggested, Chebyshev ratios of dark versus light image data sets were made, and principal component analyses of the Chebyshev images were also done. However, none of the results were particularly useful, although a density-sliced image of visible Chebyshev ratio 8/4 was helpful for discriminating wet and dry habitats (Appendix A).

RESULTS

Between the time verbal agreements were made with GER for flying the 256-channel spectroradiometer and the time the commitment was made to go ahead with the project, GER had installed its newly developed 63-channel airborne imaging scanner (GERAIS) in its aircraft and had off-loaded the software for the old spectroradiometer. As no instrument similar to the old one was available, and as GER was unable to install the old spectroradiometer in its aircraft and bring up the accompanying software, the decision was made to have the field areas flown with the GERAIS. The new instrument is more sophisticated than the old instrument and provides image data rather than line data, generally an advantage in minerals exploration of arid areas where finding outcrops is not a problem. The GERAIS data are high-quality image data with spectral and spatial resolution far better than those of such imaging systems as the Landsat Thematic Mapper. However, the spectral resolution of the GERAIS as flown for this program was 15 nanometers (nm) in the visible wavelengths and 16 nm in the infrared, far coarser than the 1.4 nm of the old instrument. Therefore, few of the usual techniques for geobotanical minerals exploration were applicable with this new data set. In addition, because standard techniques for image analysis were designed for arid areas such as the western United States, none of those methods could be used without modification and testing. For example, the ratios that best delineate alteration zones were developed for areas of exposed outcrop, not dense vegetation, and the first principal component no longer recognizes topography in the heavy vegetation of the field area. As a result, old techniques were modified and new techniques were developed, some of which are still being tested.

Some knowledge of field conditions, i.e., "ground truth", is needed whenever a new technique is being used. Because of the different nature of the data gathered by the old GER spectroradiometer and the fact that the old instrument had been tested previously for minerals exploration purposes in another vegetated area, ratios of Chebyshev data from that instrument could have been tested for their ability to locate areas of stressed vegetation in Minnesota without prior field checking. The data from the spectroradiometer were strictly spectral, and no images were created. If those data had showed nothing of interest on a preliminary run, then field data or vegetation maps would have been needed for further study. In this case, the new instrument being flown over the field areas had never before been used for minerals exploration of heavily vegetated areas. Therefore, field checking of vegetation and preparation of some vegetation maps was necessary in order to examine differences observed in the data and to provide training sites for supervised classifications. Since the LCMR biogeochemical prospecting project was collecting ground truth data, these data were used to assist in the interpretation of the airborne spectral data given in this report.

The 16-bit spectral data from GERAIS were radiometrically corrected and converted to 8-bit data, which is the format used in most image viewing systems. Standard image processing techniques were employed to produce color-infrared images of both flight lines for preliminary study. Subsets were created for the specific sites of interest on each flight line, in order to focus on the field sites themselves and avoid nearby roads, bodies of water, and other distracting features. Site specific processing was then done, as outlined below.

Site A - Dunka Pit

After preliminary imagery for Site A was examined, a number of problems inherent to the site were noted. The area of contamination for which geochemical analyses were available (Seep 3 - Appendix D) was so small that it covered only a few pixels, most of which were shared with surrounding non-contaminated or non-vegetated areas (for example, the mine dump - Plate 1). The highly reflective mine dump was so close to the seep that its strong signal overwhelmed the weaker reflectance of the vegetation in the contaminated area. In addition, no recent ground truth was available at the time the processing was done to confirm vegetation types and conditions in the area. Most significantly, however, as discovered during field work, was that the environmental damage in the seep area had increased since it was last examined by the Minerals Division of the Department of Natural Resources, and most of the trees in both the high- and medium-nickel areas were dead. Consequently, any vegetation signal received for the contaminated area would be from dead trees and underlying moss and herbs, and would not be at all comparable to the vegetation signal for control areas. For these reasons, no additional processing was done on this site.

Site B (Eastern end of Archean flight line)

This site has known gold and base metal mineralization but in sub-economic amounts. This site was selected to test whether the presence of metallic mineralization produced detectable stress in the vegetation.

The image for this site was subset to remove most of Shagawa Lake, Burntside River, and roads and railroads to the south and east, leaving as an image focus the field site with the grid area (Appendix D). Many image products were generated for analysis of GERAIS data, including the standard color-infrared and color ratio composites, as well as principal components, inverted principal components, unsupervised classifications, and Chebyshev ratios and principal components. A general description of each image type may be found on pages 16-18.

The CRC that was most useful for site analysis was $23^2/7$, $19^2/15$, and $7^2/15$. Numerators were squared to maximize differences between vegetation types. The principal components analysis was done for four GER channels (7, 15, 19, and 23 - see Fig. 1 in Appendix A) that fall within regions of the vegetation spectrum that correspond approximately with the green reflectance peak (near 550 nanometers), the chlorophyll absorption band (around 680 nm), the middle of the long wavelength edge of the chlorophyll absorption band (around 715 nm), and the near-infrared shoulder of that absorption band (around 780 nm). The PCs were then inverted to produce IPCs for study, and a series of unsupervised classifications was done using the PC data. Plate 2A is the result of the unsupervised classification and Plate 2B is the overlay of the interpreted vegetation.

Of all the products, the unsupervised classification of the four principal components generated from channels 7, 15, 19, and 23 provided the most useful information (Plate 2A). This image identified most of the vegetation types present at Site B, except for some of the conifers, which it classed together (Plate 2B). A density-sliced image of visible Chebyshevs 8/4 provided this further separation through its apparent ability to identify upland and lowland species, possibly through detection of moisture differences. The Chebyshev polynomial expansion has been used successfully on the narrow-band data from the old GER 256-channel airborne spectroradiometer for identifying metal-stress effects in vegetation. However, the Chebyshev data from the broader band imaging scanner flights have to date yielded no useful minerals information.

Ground spectral radiometer field data for this site are discussed in the paper in Appendix A. However, a further evaluation of the data from *Populus tremuloides* at Site B warrants a few comments here.

The field data for this species indicate a possible shift to longer wavelength of the long wavelength edge of the chlorophyll absorption band in leaves of *Populus* growing on four mineralized sites (12w, 20w, 44w, 50w) when compared with background data for Site B. This shift to longer wavelengths results from a stronger chlorophyll absorption feature, indicative of enrichment, not stress. However, for a fifth mineralized site (St. Joe) which has known gold occurrence and shows gold in *Populus* in biogeochemical analyses (L. Zanko, unpubl. data), the "background" values are at longer wavelengths than the "mineralized" values. As the presumed "background" trees were all just downslope of the mineralized outcrop, it is possible that those trees were actually benefitting from a growth enhancement effect, with elements leached from the outcrop above. It is unlikely that the trees on the outcrop were exhibiting spectral effects of metal stress, as their inflection points are intermediate between those from the "background" area downslope and the background values for all other *Populus* at Site B. As there are no clear, highly significant trends consistent from point to point within Site B, the likelihood that mineralization effects on *Populus* can be detected with the airborne data is diminished.

CONCLUSIONS AND RECOMMENDATIONS

The airborne imaging scanner survey data can be useful for discriminating different types of vegetation, and for ecological studies of community change, vegetation damage, etc. However, in order to rectify and interpret the airborne data, a good knowledge of the areal distribution of vegetation types or ecological habits is important for interpreting these data initially. Once the detailed distribution of the vegetation is understood, interpretation of the airborne imaging scanner data is somewhat easier, although additional ground truth data would provide much greater confidence in the interpretation of the data. Interpretation of stressed vegetation from the airborne imaging scanner data is not yet possible and will require additional work. A similar study in a northern boreal forest of Canada by Wagner, *et al* (1989) showed that: 1) tree reflectance value is not the only factor affecting pixel intensity; 2) geochemical stress is not the only environmental condition changing the reflectance values; and 3) geochemical composition may be variable within a site. These data suggest that understanding the physical and chemical variables that control the pixel reflectance at a particular site are very important in interpreting airborne spectral data.

Therefore, the following recommendations will assist in interpreting the remainder of the airborne spectral data:

1. collection of vegetation/ecological data in conjunction with the interpretation of the airborne spectral data;
2. effective use of GIS (geographical information systems) to assist in control of the various physical variables that might affect tree reflectance;

3. collection of biogeochemical data over mineralized sites for comparison with the airborne spectral data.

Furthermore, this study shows that a spectroradiometer survey with a narrow band width and low ground spatial resolution (<5 m), such as the old GER 256-channel instrument, would be more effective in identifying areas of stressed vegetation than the 63-channel imaging scanner.

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APPENDIX A

SPECTRAL RESPONSE OF VEGETATION TO METALLIC ELEMENTS IN NORTHEASTERN MINNESOTA

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INTRODUCTION

High resolution airborne scanner data were acquired over a heavily vegetated region in northeastern Minnesota. The Geophysical Environment Research, Inc. (GER) 63-channel airborne imaging scanner* was flown in early September, 1988, over areas of both known and suspected mineralization in a structurally complex, glaciated region. The Vermilion Fault study area, in an Archean greenstone belt, is being actively explored for gold. This area was covered by a single flight line about 21 by 8 kilometers. The second, larger study area in the Duluth Complex required two lines for coverage of a 40 by 8 kilometer swath. The primary site of interest in this area contains known copper-nickel deposits, but other sites covered by the flight include suspected copper-nickel deposits and copper-nickel-palladium-platinum-gold-silver prospects. This paper concentrates on the Vermilion Fault site.

The study areas are covered by boreal forest and marsh and bog vegetation. Many plant species found in boreal forest regions are known to concentrate heavy metals. The presence of heavy metals in the soil is known to cause vegetative stresses that lead to morphological effects (stunting and reduced biomass) and species distribution changes (Milton *et al*, 1989a; 1989b). In addition, in greenhouse, field, and airborne data sets, spectral changes have been observed in plants growing in anomalous concentrations of metallic elements (Milton, *et al*, 1983; 1988). Among the changes observed in laboratory spectra of greenhouse-grown metal-dosed plants are a shift to shorter wavelength (the red edge shift) in the long-wavelength edge of the chlorophyll absorption band centered at 680 nm

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*Use of trade name is for descriptive purposes and does not imply endorsement by the U.S. Geological Survey.

and increased reflectance in the 550-650 nm region (the green reflectance peak). Ground spectral measurements were made in the Minnesota study area to determine changes in reflectance in plants growing in mineralized areas.

Geology

The study site, near Ely, Minnesota, is a heavily vegetated region having a glacial cover of varying thickness. There is little visible outcrop. Sims (1985) mapped the area as a lower mafic volcanic member, mainly basalt, with gabbroic sills, felsic-intermediate tuffs, and banded iron-formation. Mineralization occurs in massive and disseminated sulfides and gold-quartz veins.

Vegetation

Vegetation in this part of Minnesota is classified as boreal forest type and transition type (Walter, 1973). The most abundant species in the study area are white cedar (*Thuja occidentalis*), balsam fir (*Abies balsamea*), trembling aspen (*Populus tremuloides*), and paper birch (*Betula papyrifera*). Red and white pine (*Pinus resinosa* and *P. strobus*), black ash (*Fraxinus nigra*), tamarack (*Larix laricina*), black spruce (*Picea mariana*), and big-tooth aspen (*Populus grandidentata*) occur in some areas. Forested areas have dense cover, both on drier upland areas of aspen and birch and in low white cedar swamps. Even the more open peat bogs have black spruce and tamarack growing over thick sphagnum and shrub layers.

Airborne Scanner

The GER 63-channel airborne imaging scanner was flown over the field area in early fall, 1988. Spectral resolution in the visible wavelengths was approximately 15 nm, with 15-20 meter pixel size. Although the flight was originally planned for the 256-channel airborne spectroradiometer that has the very narrow channels so useful in vegetation studies, GER apparently no longer flies that instrument.

In addition to the raw data, Chebyshev images were provided by GER, 10 each in the visible and infrared regions. The images were produced by applying the Chebyshev polynomial expansion to the 24 visible and the 39 infrared channels.

Because the focus of this study was identification of vegetation growing over mineralization, we concentrated on the visible wavelengths between 510 and 800 nm, specifically bands 7, 15, 19, and 23, as significant features that indicate plant stress occur in that region (Fig. 1), and on the visible Chebyshev images.

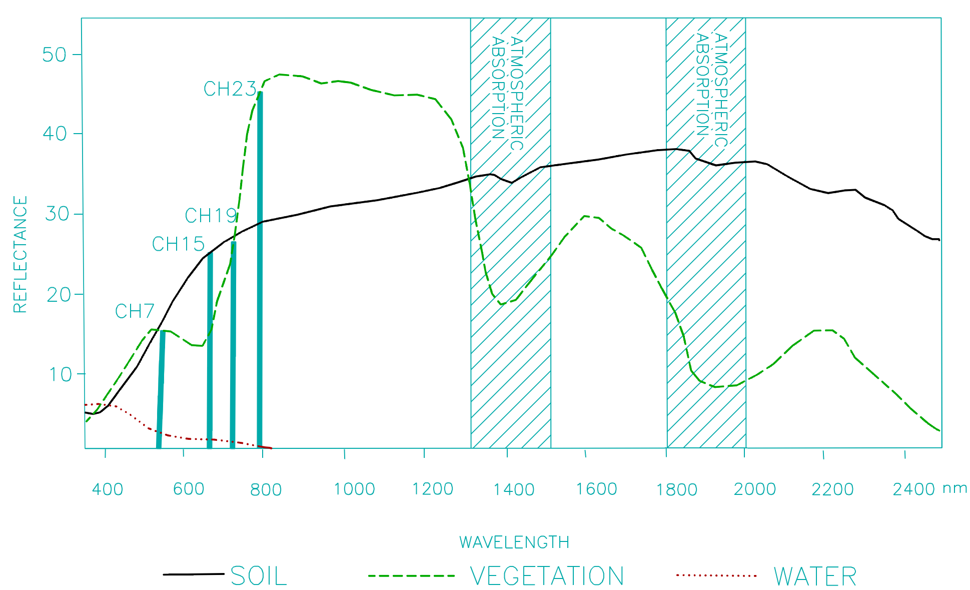

Figure 1. Typical plant and soil spectra showing locations of the airborne scanner channels used in the analysis.

FIELD SPECTRAL STUDIES

Methods

Vegetation reflectance measurements were collected at the Ely site in summer, 1989. Percent reflectance was measured using a GER Corp. Mark IV Infrared Intelligent Spectroradiometer and a Halon reference standard. The sites chosen were identified by Minnesota colleagues as having occurrences of high amounts of copper, zinc, and nickel and indications of gold and silver mineralization.

Canopy leaves of commonly occurring species were chosen for collection. Species from the mineralized sites were paired with the same species at background sites. We collected 10 spectra per species per site, using mature, undamaged leaves from at least 3 different trees whenever possible. Branches were cut, wrapped in large plastic bags, and stored on ice. Spectral measurements were generally made the same day plants were collected.

Leaves or small twigs were excised just prior to measurement and stacked to make a bed of leaves at least 6 thick or a bed of conifer branches several inches thick. The Halon standard was always at leaf surface height, and the instrument detector head was always at the same distance from the leaves.

Spectra of a single species at a site were averaged, and those from each mineralized site were compared statistically with spectra from the associated background site. To define the red edge position, inflection points of the first derivative curves for each individual spectrum were derived and compared using Student's T tests in the BMDP statistical package.

Results

Of the 9 species sampled, 3 showed no statistically significant shift of the red edge (Fig. 2). The remaining 6 showed significant shifts, but with the exception of *Carex*, the shifts were to longer wavelength (Fig. 3). These results are in contrast to the greenhouse and previous field results reported at ERIM and elsewhere (Milton, *et al*, 1983; Milton, *et al*, 1985; Milton, *et al*, 1988; Eiswerth, *et al*, 1989) in which the red edge shifted to shorter wavelength.

SHAGAWA	DUNKA	SPRUCE ROAD	MUD CREEK	LAKE
BETULA				**
CAREX	**			
FRAXINUS			**	
PICEA		**		
POPULUS		**		**
THUJA			**	

**: Significant at P < .05

Species not showing spectral shifts; ABIES, ALNUS, PINUS

Figure 2. Species showing statistically significant shifts of the red edge. Comparisons were made of the locations of the inflection points on the 1st derivatives of the field reflectance curves.

Other spectral changes were consistent with the long-wavelength shift and in contrast to the previous work. Reflectance was lower in the green and yellow spectral regions (500-650 nm) (Fig. 3), and reflectance was variable on the infrared plateau (780-1000 nm).

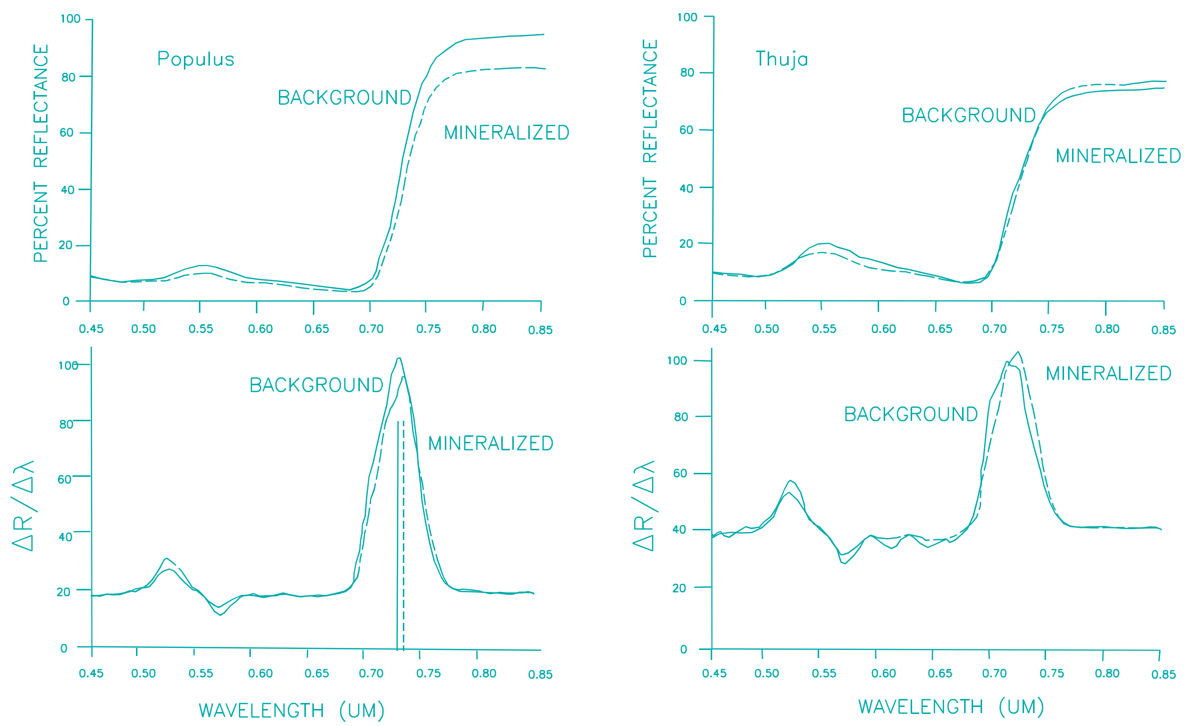

Figure 3. Spectral reflectance curves and 1st derivative curves of two species from mineralized and background sites, showing the shift of the red edge to longer wavelength.

Reasons for the long-wavelength shift are unclear and need further study. In greenhouse studies, selenium-treated plants displayed long-wavelength shifts. Horler, *et al* (1983) demonstrated a shift to longer wavelength with leaf maturity. Salisbury, *et al* (1987) illustrated this idea by showing the effect of increasing saturation of an absorption feature. This might occur as the leaf matures and its chlorophyll content increases. The effect on the long-wavelength edge gives the appearance of a shift to longer wavelength. Increased chlorophyll could be the result of a growth enhancement effect on certain species growing over a mineralized area. When conditions are favorable, the elements may act as nutrients rather than as toxins. This might occur given a particular combination of soil, water, pH, and microclimate.

AIRBORNE STUDIES

Methods

Imagery produced using visible channels 7, 15, 19, and 23 included color-infrared, color-ratio-composite, principal components, and inverted principal components products. A minimum distance classification was done using principal components of the 4 visible channels. In addition, we produced several images using the 10 Chebyshev data sets.

Results

Of particular usefulness in identifying forest cover type was the unsupervised classification using the 4 principal components. The resulting image separated coniferous forest, upland aspen/birch forest, black ash swamp, sedge marsh, open meadows or areas with bare soil showing through, and mixed forest areas. Most significantly, areas with open forest canopy were readily separable from closed or dense canopy and often these open canopy areas corresponded with canopy damage of presently unknown causes. Future work using this classification will focus on separating open canopy from damaged canopy and on separating mechanical damage (insects, logging) from chemical damage (mineralization, pollution).

At GER's suggestion, we ratioed several of the Chebyshev data sets and did a principal components analysis of all 10. Of these analyses, a ratio of Chebyshev images 8/4 proved most useful. This ratio apparently is sensitive to moisture differences, and clearly separated upland conifer from lowland conifer forest, and upland from lowland deciduous forest. This image in combination with the classification discussed in the previous paragraph will provide the canopy composition information required for identification of areas of canopy damage, and ultimately of potential mineralization effects.

SUMMARY

Vegetation at the field site is highly disturbed by logging and other human use, with either very mixed stands or small one- or two-species stands of only a few pixels in size. Such small vegetation communities are barely above the spatial resolution limits of the airborne instrument. In addition, the spectral resolution of that instrument as it was flown is not fine enough to detect the red-edge shift.

Given these factors, we plan to examine other spectral changes that may occur in vegetation growing over mineralization. We will look more closely at overall canopy differences for evidence of stress effects rather than concentrating on fine spectral characteristics. In addition, plant community differences at the site will be examined for their ability to provide geological information. We also will examine the question of the direction of the red-edge shift in further greenhouse and field experiments.

The field spectral data, vegetation maps, and the classification and Chebyshev ratio images will be incorporated into a GIS system along with new field geochemical profiles to be provided by our Minnesota colleagues. To this information base we will add results of future field and laboratory work.

APPENDIX B

AIRBORNE IMAGING SCANNER
DATA TAPE INFORMATION SHEETS

The three flight lines required a total of eight data tapes. Tapes 1-1 and 1-2 start southwest of Dunka Pit and go southwest; tapes 2-1, 2-2, 2-3 start just northeast of Filson Creek and go southwest to beyond Dunka Pit, and tapes 3-1, 3-2, and 3-3 start in Shagawa Lake near Boulder Bay and go west/southwest to Armstrong Bay, Vermilion Lake (see Table 3).

The following information may be helpful. (Use tape 1-1 as an example and its scanner data tape information sheet as a guide to file names.)

To mount the tape, use the tape label "GER".

To process channel 1 of the data, call up file name M1GRES_1.dat. Files (and channels) are in alphanumeric order so that tape 1-1 contains files M1GRES_1 and 11-19, M1GRES_2 and 21-29, and M1GRES63, 7, 8, and 9, as well as some Chebyshev data. Tape 1-2 contains files M1GRES_3, 31-39, 4, 41-49, 5, 51-59, 6, 61-62, and thus the channels with those numbers. The Chebyshev data are described in the text and are not useful for general purposes. There are ten Chebyshev files for the visible wavelengths and ten for the infrared wavelengths.

Under "Data Format" at the bottom of each sheet, "integer *2" means that the data are 16-bit. There are 512 pixels per record and 1554 records per file; that is, the data sets are 512 by 1554 pixels each on tapes 1-1 and 1-2.

The data tapes are available from the following address for the cost of the tapes and reproduction:

Minerals Division
Center for Applied Research and Technology Development
Natural Resources Research Institute
University of Minnesota, Duluth
5013 Miller Trunk Highway
Duluth, Minnesota 55811

APPENDIX C

GER CHANNEL WAVELENGTHS AND RADIANCE CORRECTIONS

Each channel is listed with its wavelength and a radiance correction function. The scanner measures radiance, but because different detectors are used for different wavelengths, there may be instrument sensitivity differences. Therefore, after laboratory instrument calibration, GER provides a gain for correcting the radiance value of each pixel.

APPENDIX D

GEOCHEMICAL AND BIOGEOCHEMICAL GROUND TRUTH DATA FOR VARIOUS SITES WITHIN THE FLIGHT LINE AREA

List of Files on Diskettes

Diskette 1

Dunka Pit - Seep 3

Tdunka.wk1	8,033 bytes - vegetation data
Edunka.wk1	2,533 bytes - soil data

Raspberry soil geochemistry

Rasp.wk1 116,784 bytes

Rasp.dxf - CAD drawing file of Raspberry grid locations for soil data

Diskette 2

Soil geochemistry from the Minnamax site from Department of Natural Resources Minerals Division project 68-1 - 445 grid points

Soil.wk1 - grid location data and soil physical characteristics
Geochem.wk1 - (ppm) Ag, Cd, Co, Cu, Mo, Ni, Pb, Zn, Mn-(wt.%) Fe