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Introduction

This paper describes a preliminary experiment that was made to compare the spectral reflectance from trees growing in soil over a mineral deposit with reflectance from trees of the same species growing in a nearby unmineralized area. Although the measurements were made on a relatively small number of trees, some significant differences were obtained and the overall results are encouraging enough to warrant additional studies. Preliminary results suggest that measurement of spectral reflectance may become a dramatic new way of detecting geochemical soil anomalies by remote means in tree-covered areas.

Traditional prospecting methods, wherein rocks are examined directly for valuable minerals, can no longer be expected to produce many important mineral discoveries, except possibly for those deposits of minerals that were of little or no economic interest until recently. Most areas of the world amenable to this type of prospecting have been examined repeatedly by several generations of prospectors. However, in large areas, rocks and geologic structures favorable for the occurrence of ore are concealed beneath soil and alluvium. In such areas many important ore discoveries have been made in recent years by utilizing the newer geochemical and geophysical prospecting methods. And, it is reasonable to assume that in such areas many future mineral discoveries will be made as we refine existing exploration methods as well as develop new ones.

In the past 20 years, geochemical prospecting has progressed from a little-used and often-scorned technique to one that is widely used in most modern-day exploration programs. At present, geochemical soil sampling methods have been perfected to a higher degree than most other geochemical techniques. In areas of residual soils, the identification of an area of soils having abnormally high amounts of certain metals furnishes a strong clue as to the possible presence of a nearby concealed mineral deposit. To locate and delineate many metal anomalies in soil requires that large numbers, often many thousands, of closely spaced soil samples be collected and analyzed for one or more trace constituents. In most parts of the world such soil-sampling programs are becoming increasingly expensive. Developing

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a method of detecting such anomalous areas by appropriate sensors mounted in aircraft, or even in orbiting satellites, would constitute an important breakthrough in mineral exploration and might dramatically reduce exploration costs.

In considering ways of sensing abnormal chemical conditions in the soil by remote means, the possible use of vegetation is, for two reasons, a natural avenue to explore. First, data from many biogeochemical surveys performed during the past few decades have shown that plants growing in a geochemically anomalous soil generally reflect this in their trace element content; and, sometimes, these plants show characteristic variations in their form, color, size, or rate of growth. Second, the forest canopy is easily visible to a sensor in a plane or satellite.

Interrelationships between a tree and its environment are complex, and many nongeological parameters, of course, affect plant health, growth, distribution, and composition; nevertheless, the geologic environment is one of the more important environmental parameters. Chlorosis is a common diseased condition of chlorophyll-bearing plants characterized by absence of or deficiency in green pigment and manifested typically by a yellowing of the leaf which in turn causes the green veins to stand out prominently. Chlorosis can be caused by the presence, in excessive amounts, of elements that are antagonistic to iron in plant metabolism and that interfere in the production of chlorophyll. Although other causes of chlorosis are fairly common, prospectors and geologists have long known that a chlorotic patch of vegetation may indicate an area of metal-rich soils or rocks and therefore merits their attention.

Actually, mineral-deposit-related chlorosis is rather rare in virgin environments. While different plants seem to vary greatly in their ability to tolerate excesses of various elements in their nutrient solutions, the concentrations of most elements required in the supporting soil to produce symptoms visible to the unaided eye are often fairly high. Further, in areas of many geochemical soil anomalies that are genetically related to important mineralization, the vegetative canopy is apparently healthy, no toxic symptoms being visible to the eye. It is possible, however, that the abnormal chemical environment causes subtle--but nevertheless definite--changes in some physical or chemical aspect of one or more plant organs. These changes, if detected and quantitatively measured, can then serve as an indicator of an abnormal chemical environment at the tree roots. Because many common ores contain elements known to be antagonistic to iron in plant metabolism, it appears resonable to assume that such excess metal content might induce incipient chlorosis, a condition identifiable from measurements of the spectral reflectance. Other variables, of course, affect spectral reflectance but if their effect can be accounted for satisfactorily, trees should be useful as sensors of geochemical soil anomalies.

Published spectra of vegetation are scarce and no data are known in the literature that would indicate whether the spectral reflectance of apparently healthy trees in a geochemically anomalous area differs significantly from the spectral reflectance of trees growing in areas of normal elemental content. Therefore, an experimental plan was designed to measure spectral reflectance of trees growing in anomalous and in background areas under natural conditions, wherein tree targets would be viewed and measured much as an aerial camera or other type of airborne spectrometer would view them.

The work on which this report was based was supported by the National Aeronautics and Space Administration (NASA). The Geological Survey contributed the chemical analyses of the soils and vegetation. The overall direction of the project was by F. C. Canney, who was also responsible for the selection of the site, the trees to be measured, and the geologic and geochemical ground control analyses. The reflectance measurements in the field, the reduction of the data, and the statistical study were done by the Science Engineering Research Group of Long Island University under the direction of Prof. Edward Yost.

Previous work

An appreciable amount of research is currently underway on the applications of remote sensing to problems in forestry and agriculture and has been reported in the literature. By comparison, very few experiments specifically directed to the mineral exploration field appear to have been done. In the highly competitive mineral industry, industry-sponsored experiments of this nature would very rarely be reported anyway in the scientific literature, especially if results were encouraging enough to suggest that a new exploration tool might be forthcoming. The concept that spectral signatures of vegetation might be useful in the detection of biogeochemical anomalies genetically related to mineralization has apparently occurred independently to various individuals. During the past 6-8 years several aerial reconnaissance surveys were flown by several organizations over mineralized structures in forested areas; the sensor used was false-color infrared film. Available information suggests the results were not generally felt to be encouraging. This was certainly my appraisal after making several experimental aerial surveys in 1966 and 1967. Admittedly, most of these surveys, including my own, were not made under closely controlled conditions.

The experiment closest in scope to the one described herein was executed by C. E. Olson, Jr., of the University of Michigan, and H. T. Shacklette of the U.S. Geological Survey, in 1962. They collected leaves from a variety of deciduous trees rooted in both geochemically anomalous and background areas in the southwestern Wisconsin lead-zinc district, and then they measured their spectral reflectance. Although the experiment unfortunately had to be recessed, reduction of the data has been resumed by Olson and the data are expected to be available in the near future.

Selection of test site

The test site selected was Catheart Mountain in west-central Maine, where a large but low-grade copper-molybdenum deposit was discovered a few years ago by private investigators. It seemed to be an appropriate test site for the following reasons:

1. The area is still largely undisturbed by man.
2. It is completely forested with both deciduous and coniferous trees.
3. Detailed and extensive geochemical ground control is available.
4. Large areas of soil contain highly anomalous amounts of copper and molybdenum, which are also anomalously concentrated in the trees.
5. The major geochemical soil anomaly encompasses an area about 1 mile square, a target large enough for possible later experiments from orbital altitudes.

The area is slightly more complex, both botanically and geologically, than was desirable for a first test, but that disadvantage was far outweighed by the advantages.

Field procedure

For the initial experiment balsam fir (Abies balsamea (L) Mill) and red spruce (Picea rubens Sarg.) were selected as the species to be examined. Five specimens of each species growing in the anomalous area of metal-rich soils were measured and compared with similar specimens growing in a nearby unmineralized area. So far as possible, other factors--such as soil type, soil moisture, and exposure--that might affect reflectance were kept constant between the two groups. A sample of the foliage of each tree and a sample of the supporting soil in which it grew were collected for chemical analysis.

Each tree spectra consisted of 27 measurements of reflected radiation, and 27 measurements of simultaneously incident solar radiation, made at each wavelength. The wavelengths were spaced at 25-nanometer intervals in the 350- to 750-nanometer region and at 50-nanometer intervals in the 750- to 1100-nanometer region. Reflected radiation greater than 1100 nanometers could not be recorded because overcast conditions prevailed during much of the test period. Each tree was scanned three times and the average values of reflected and incident radiation were used to compute the percent directional reflectance.

To make the reflectance spectroradiometric measurements meaningful for possible future experiments using an aerial sensor, the spectroradiometer was placed above the tree so the measurements were obtained in a downward-looking orientation. This was accomplished by placing the instrument in the bucket of a "cherry picker." Figure 1 shows the method used to obtain reflectance spectra. Extreme care was taken to ensure that the field of view of the tree being measured was completely full so unwanted radiation from the background would not leak into the optical system.

Results

The spectral reflectance curves for red spruce and balsam fir are shown in figures 2 and 3 and the chemical data in tables 1 and 2. The vegetation samples collected for analysis were of 1- and 2-year-old needles and twigs composited from the general area of the tree imaged by the spectroradiometer. Copper and molybdenum analyses are expressed as parts per million (ppm) in the vegetation ash. The amount of ash of the dried plant material ranges from 2.5 to 3.5 percent.

The curves for both anomalous and background groups of red spruce (fig. 2) are essentially the same in the visible region of the spectrum. In the near infrared, from 750 to 1100 nanometers, the anomalous group shows a uniform pattern of decreased reflectance. This was, of course, the result we had hoped to find. Actually though, while the spectral differences are highly encouraging, the values are not significantly different at the 95-percent confidence level.

The chemical data for red spruce, shown in table 1, reveal that, unfortunately, the trees selected for measurement were growing, for the most part, in soil only slightly anomalous in copper and molybdenum. And though all spruce trees of the anomalous group were weakly anomalous in molybdenum, only one tree (no. 5) was anomalous in copper. In this preliminary study, however, the selection of trees was severely hampered by the restricted mobility of the cherry picker on a rough mountainside.

The reflectance curves for balsam fir (fig. 3) show a marked contrast with those of spruce. At every wavelength the anomalous fir group had a higher reflectance than the background group. The statistical analysis of these data showed that in the 525-750 nanometer region the difference was significant at the 95-percent confidence level. From 750 to 1100 nanometers, the difference would have been significant if the spectra of one tree (no. 15) had been deleted from the data set. The balsam fir group (table 2), on the whole, were rooted in soils that contain distinctly more copper and molybdenum than the spruce-group soils.

The inferences to be drawn from these data are limited by the small sample size and by the relatively large variance of the data, especially in the 750- to 1100-nanometer region of the spectrum. There is a strong suggestion, however, that the effect of metal-rich soils on the spectral signatures of trees may be quite variable between species. As judged from the described experiment though, multispectral photographic techniques could probably be used to separate balsam fir trees with anomalous metal contents from the other tree groups sampled. The present results are encouraging enough to warrant additional studies. The continuation of this research should ultimately lead to a new way of detecting mineral deposits by remote means.

Table 1

METAL CONTENT OF RED SPRUCE (AND SUPPORTING SOIL)
USED FOR REFLECTANCE MEASUREMENTS

	SAMPLE NO.	PARTS PER MILLION			
		COPPER		MOLYBDENUM	
		VEG. ASH	SOIL	VEG. ASH	SOIL
ANOMALOUS GROUP	1	120	115	8	10
	2	120	115	8	10
	3	150	225	8	20
	5	230	60	20	75
	6	120	60	8	40
BACKGROUND GROUP	13	150	5	3	3
	16	150	5	3	5
	17	150	5	3	5
	18	120	5	5	<3
	19	120	<5	5	<3

Table 2

METAL CONTENT OF BALSAM FIR (AND SUPPORTING SOIL)
USED FOR REFLECTANCE MEASUREMENTS

	SAMPLE NO.	PARTS PER MILLION			
		COPPER		MOLYBDENUM	
		VEG. ASH	SOIL	VEG. ASH	SOIL
ANOMALOUS GROUP	4	150	115	60	150
	7	450	2250	225	150
	8	450	2250	225	225
	9	300	15000	150	75
	10	450	9000	60	80
BACKGROUND GROUP	11	150	30	5	8
	12	120	5	3	3
	14	120	<5	3	3
	15	150	5	3	3

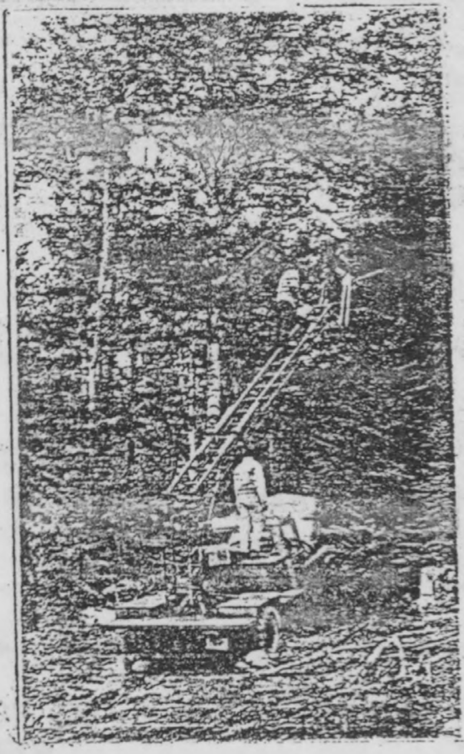

Figure 1.--Photograph showing method of obtaining reflectance data in a downward-looking orientation.

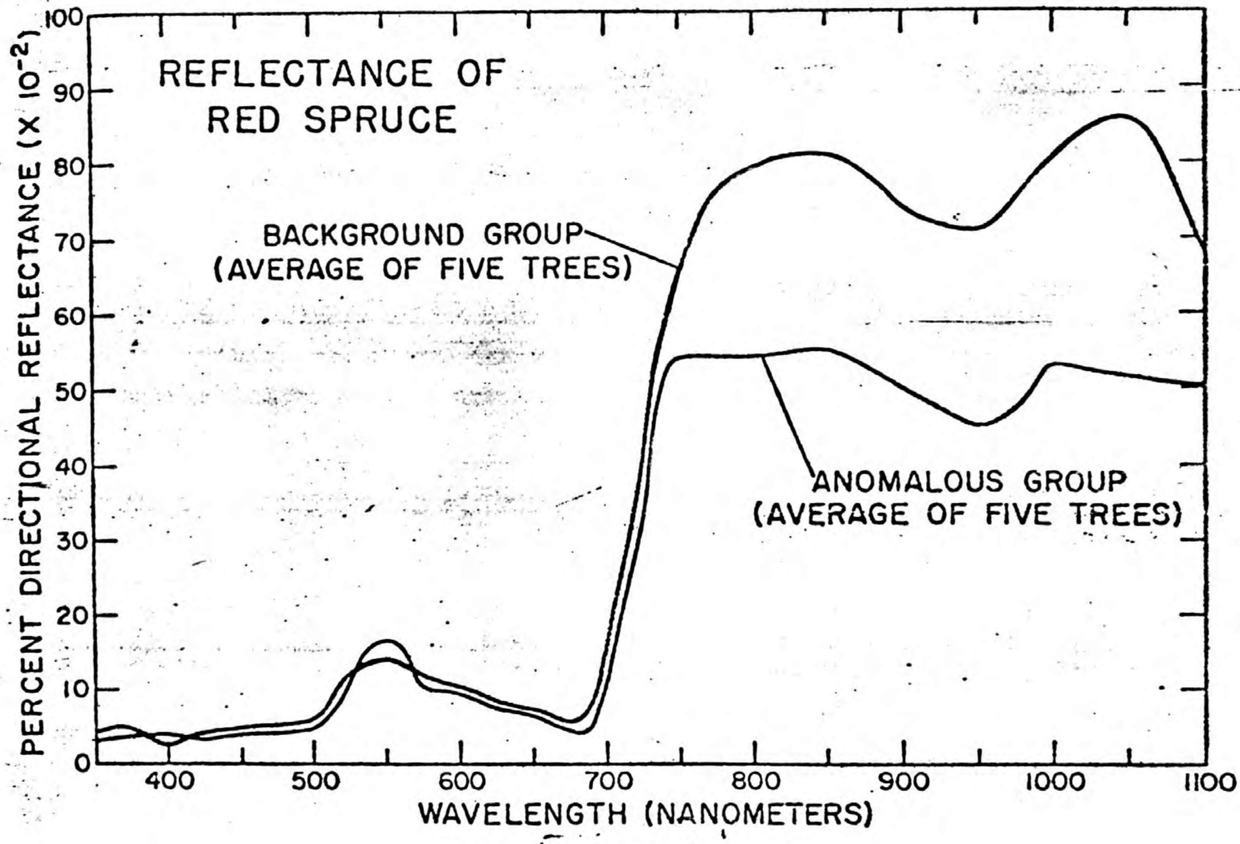

Figure 2

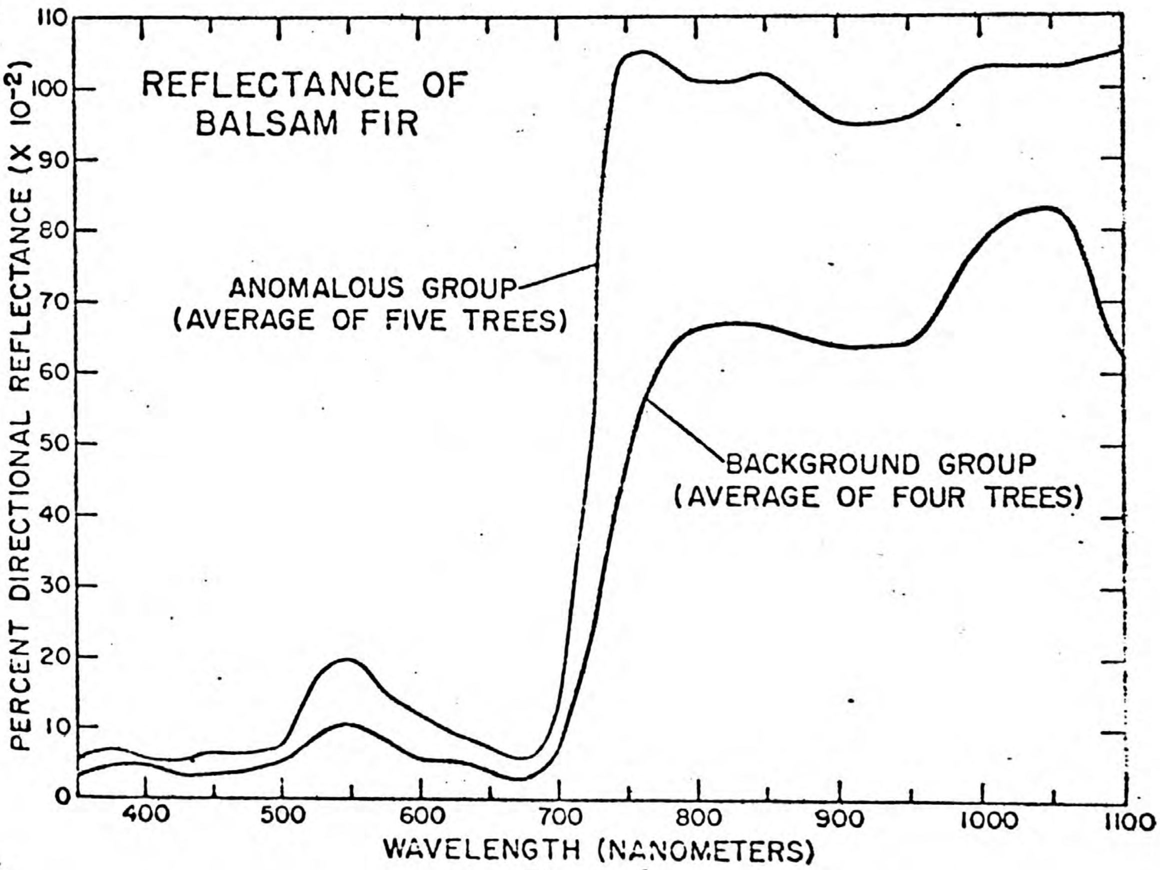

Figure 3 .