GEOBOTANICAL TECHNIQUES FOR DISCRIMINATING SERPENTINE ROCK TYPES IN WESTERN UNITED STATES

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ABSTRACT

Serpentine-derived soils have a significant affect on species composition, vegetation density, and vegetational spectral response as a result of several factors including low calcium/magnesium ratios and high concentrations of chromium, cobalt, and nickel.

Remote sensing techniques involving airborne scanner imagery and several statistical and image processing techniques were used in three diverse test sites in western United States to discriminate vegetation parameters associated with serpentine rock types.

Vegetation parameters which were found to be most useful for discriminating the serpentine rock types included species composition changes and density. In general, more xeric vegetation types occur within the areas of serpentine. In regions of mixed woodland and forest, serpentine soils tend to be characterized by coniferous tree species while in semiarid terrain, serpentine soils are characterized more by shrubby than by grassy species. These broad vegetation differences and more specific vegetation types were readily discriminated by the remote sensing analysis. Useful techniques involved relatively simple visual image analysis, contrast stretching of individual bands, stepwise discriminant analysis, and principal components analysis.

INTRODUCTION

Vegetation on serpentine soils is commonly sparser and of different composition than the vegetation occurring on neighboring non-serpentine soils. This phenomenon has been reported from various locations around the world, including New Zealand, Poland, the Soviet Union, and the United States (Whittaker, 1954; Brooks, 1972). The identification of serpentine and the host ultramafic rock types is of considerable interest as they commonly contain economic deposits of metals such as Cr, Ni, and Co.

There are several distinctive properties of serpentine soils that are adverse to the growth and development of many plant species. Serpentine soils are usually low in Ca and high in Mg. Both of these elements are

are required by plants and absorbed by the roots as divalent ions. In some instances, the low Ca concentration may result in a nutrient deficiency. In other instances, the similar size of these ions results in the plants not being able to selectively absorb enough Ca without suffering Mg toxicity. One of the proposed mechanisms by which plants may be able to adapt to serpentine soils is an ability to preferentially absorb Ca over Mg (Walker et al., 1954).

Serpentine soils are also quite high in Cr, Ni, and Co. These elements are not known to be required in plant nutrition, and in fact, rank as among the most toxic of all elements to plants even though they are nearly insoluble in soil solutions (Brooks, 1972). In addition, serpentine soils are low in plant nutrients such as Nitrogen, potassium, and molybdenum (Walker, 1954). Finally, serpentine soils tend to be drier than adjacent non-serpentine sites on account of shallow development and gravelly textures.

In most situations, it is likely that it is some combination of these factors that accounts for the effect of serpentine on local vegetation. Variation in the bulk composition of the parent material can likely result in an increased or decreased effect on the vegetation. Where the content of Cr, Ni, or Co is unusually high, for example, the adverse effect might be expected to increase. Species compositional differences in the natural vegetation with serpentine areas may provide valuable clues in mineral exploration.

The authors are currently involved in an investigation of several serpentine areas near the west coast of the United States. We are combining ground based examination of vegetation, rock types, and soils with the use of multispectral airborne scanner imagery. Our interest is to evaluate the utility of such imagery to identify and map areas of serpentine and to detect variations within the serpentine that may have exploration significance. This paper describes preliminary results involving the delineation of serpentine areas.

SOUTHWEST OREGON STUDY AREA

The southwest Oregon study area is located within the Siskiyou Mountains adjacent to and north of the California and Oregon border and approximately 40 km (on average) from the Pacific Ocean. The region is known for its unique vegetation and geology. A wide diversity of vegetation types has been recognized as occurring in relation to the steep climatic gradients and diverse parent materials of the region. Elevations within the study area range from 400m to over 1500m. The climate is strongly influenced by maritime air from the Pacific Ocean and has cool winters (mean January temperature is 5 degrees C) which are characterized by abundant precipitation (over 200 cm annually) and mild dry summers (the mean July temperature is 20 degrees C).

The study area's vegetation follows the distribution of vegetation zones as described by Franklin and Dyrness (in Mouat et al., in press). This zonal outline follows:

Zone	Dominant species or genera
Interior Valley Zone	Pine (*Pinus* sp.), Oak (*Quercus* sp.) Douglas fir (*Pseudotsuga menziesii*)
Mixed-Evergreen Zone	Douglas fir - sclerophyll shrubs
Mixed Conifer Zone	Pine, Douglas fir, Incense cedar (*Calocedrus decurrens*)
White fir Zone	White fir (*Abies concolor*)

Serpentine vegetation occurs within all of these zones. At the lowest elevations, it differs from the surrounding vegetation by having virtually no broadleaved evergreen tree species. The vegetation often consists of a very open Jeffrey pine (*Pinus jeffreyi*) mixed grassland type often with scattered manzanita (*Arctostaphylos sp.*). This contrasts with the much denser surrounding vegetation which usually has an important broadleaf tree component. At somewhat higher elevations (approximately 600m), other coniferous tree species are present in the serpentine flora. The understory often has an open cover of broadleaf tree species which are highly stunted. At this elevation, non-serpentinized peridotite becomes an important associated ultramafic rock type. This parent material can be vegetationally differentiated from the serpentine vegetation by the much denser sclerophyll shrub and stunted broadleaf evergreen tree understory (Figure 1 illustrates this difference). At higher elevations (approximately 1,000m) the serpentine flora is distinct from the surrounding flora by certain indicator species, many of which are stunted, and a scattered shrub-grass understory. The broadleaf tree component, which is so typical of the surrounding non-ultramafic rocks is virtually absent. Trees which typically grow upon the higher elevation serpentine rocks include Port Orford cedar (*Chamaecyparis lawsoniana*), Jeffrey pine, incense cedar, western white pine (*P. monticola*), sugar pine (*P. lambertiana*), and Douglas fir.

Image Analysis

The primary imagery used in the analysis consisted of color and color infrared aerial photography at scales varying between 1:15,840 and 1:130,000, and high altitude multispectral scanner imagery. The latter was acquired by the NASA Ames Research Center over the study area on September 11, 1981. It was made with a modified Daedalus DEI-1260 scanner with ten operating channels in the visible, near IR and thermal infrared (Table I). The imagery was acquired at an altitude of 20,000m and , with a 1.25mrad IFOV, has a ground resolution of approximately 25m X 25m.

The aerial photography was useful for separating the serpentine-bearing rock types from the non-ultramafic rock types. A simulated false color composite (FCC) made from the airborne scanner imagery was also useful for separating those rock types. However, it required a ratio color composite (made from ratioing the near IR to the red band, the red to a green band, and the green to a blue band) and an enhanced 2.05 - 2.35 channel to separate the serpentine from the non-serpentinized peridotite. A modified unsupervised classification employing extensive ground data has been successful in a limited area in separating those rock types. Attempts at using principal components analysis techniques have so far not been successful for separating the serpentine from the non-serpentinized peridotite. Further attempts will be made with this technique.

JASPER RIDGE STUDY AREA

The Jasper Ridge Biological Preserve of Stanford University is located 50km south of San Francisco and is situated on a low lying ridge on the eastern flank of the Santa Cruz Mountains. It is bounded on the west by the San Andreas Fault. Elevations within the study area range from 70m to 190m. The study area receives most of its precipitation (approximately 70cm annually) in the winter. Temperatures rarely reach freezing. Geologically, the ridge consists of greenstone, chert, graywacke, and serpentine of the Jurassic-Cretacous Franciscan Formation and the Eocene Butano sandstone (Page and Tabor, 1967).

The top of the ridge is a broad gently roll-ng plateau covered with grassland. The surrounding north and east facing slopes are covered with oak-woodland. South and west slopes are covered with chaparral. This distribution is largely due to differences in moisture availability.

The chaparral on non-serpentine sites forms a dense shrubland dominated by chamise (Adenostoma fasciculatum). A number of other shrubs are associated with the chamise. There is virtually no understory beneath the shrub layer. Along the border of the chaparral with the grassland there is often a fringe of California sage (Artemisia californica) from one to three meters wide. The chaparral growing on serpentine is marked by a pronounced decrease in plant density. There is also a decrease in variety of shrubs present. The vegetation is dominated by chamise and leather oak (Quercus durata). Minor amounts of toyon (Photinia arbutifolia) and Ceanothus sp. are present. Soap plant (Chlorogalum pomeridianum) is abundant in the understory. There is no fringe of California sage at the border with the grassland. Leather oak is largely restricted to the serpentine sites. It is a scrubby plant less than three meters in height.

The grassland on non-serpentine sites is dominated by a number of introduced species. Except for soft chess (Bromus mollis), these introduced species are unable to become established on the serpentine. As a result, the serpentine grassland area has become a refugia for a wide variety of native prairie plants that are unable to successfully compete with the introduced species on the non-serpentine sites. Native plants on the serpentine grasslands include perennial bunchgrasses and numerous flowering spring annuals.

Image Analysis

High altitude multispectral scanner imagery was acquired over Jasper Ridge on October 16, 1981 and on April 23, 1982 (Table 1). The two flights employed somewhat different spectral configurations.

The vegetation conditions for the two image dates were quite different. In October, the grasslands were completely senesced and were brown, the chaparral was still dormant after the annual summer drought, and the oaks were damaged by a summer moth infestation. On April 23, the grasslands were at their annual peak in green biomass, the chaparral was actively growing, and the oaks had many new leaves.

A serpentine unit was clearly visible within the oak-woodland as a canopy opening. The serpentine chaparral is distinctive from non-serpentine chaparral on the ground and discernable on the scanner imagery. It is also possible to distinguish the dense rim of leather oak and the sparse interior features of the main area of serpentine chaparral. These features form a spatial anomaly on the imagery that is not present anywhere else.

The grassland sites show a dynamic phenological change between the two images. In the October imagery, when the vegetation on the grasslands had senesced, the visual difference between the two areas is faint. At the time the April imagery was acquired, the serpentine grassland was carpeted with goldfield (Lasenthia californica), make it quite distinctive from the non-serpentine grassland (Figure 2). To examine the effect that flowering goldfields have on the imagery, training sets for both grasslands were extracted for the two image dates. The training sets were analyzed with stepwise discriminant analysis (BMDP-7M). While the bandpasses for image data for the two flights are not identical, there is a general correspondence that makes the comparison useful. The results for the analyses are given in Table 2.

In the October imagery, the second green channel and an infrared channel were selected as being the most useful bands for discriminating the two types. The classification accuracy was approximately 80%. In the April imagery a classification accuracy of 100% was reached with the red channel. The red radiation was being strongly absorbed by chlorophyll pigments in the non-serpentine grassland, whereas the red radiation was strongly reflected by the carpet of yellow goldfield flowers on the serpentine. This phenomenon is short lived as the goldfields are only in bloom for a period of three weeks.

SIERRA NEVADA FOOTHILLS STUDY AREA

The Sierra Nevada foothills study area is located 160 km east of San Francisco in Calaveras and Tuolumne Counties. This area is physically similar to Jasper Ridge. Elevations range from 300 to 600 meters. Annual precipitation averages about 60 cm, coming mostly as winter rain. Winters are somewhat cooler than on Jasper Ridge and are similar in temperature to the southwest Oregon study area. The vegetation consists of a mosaic of grassland and oak-woodland of varying density, and chaparral.

Image Analysis

High altitude airborne scanner imagery was acquired over the Sierra Nevada foothills study area on April 23, 1982. The imagery is similar in configuration to the April imagery acquired over Jasper Ridge (Table 1). The vegetation in the foothills on this date was near its peak of green biomass, similar to the conditions on Jasper Ridge.

The study area consists of Jurassic-Triassic metavolcanics, Upper Jurassic metasediments, undifferentiated Mesozoic ultramafic intrusives (primarily serpentinized), and the Pliocene Table Mountain andesite (Jenkins, 1966; Clark and Lydon, 1962; Taliaferro and Solari, 1948). The metasediments and metavolcanics are covered by oak woodland and grassland. Figure 3 illustrates the vegetation on a typical metavolcanic area. Serpentine areas are covered by an open *Ceanothus* sp. chaparral with scattered digger pine (*P. sabiniana*)(see Figure 4). The ground between the *Ceanothus* sp. individuals is sparsely covered by the same annual plants occurring on the serpentine grasslands on Jasper Ridge. Monkeyflower (*Mimulus cutatus*) is abundant along streams and moist drainages. The Table Mountain andesite is covered by a sparse grassland cover with widely scattered digger pine. The species present in the andesite grassland are similar to those located on the nearby serpentine.

The scanner imagery was processed to form a false color composite for use in the field. On the false color composite (FCC), the non-serpentine grasslands and oak woodlands are represented by various shades of red. The serpentine areas, however, are brown. Although the andesite has a similar color, it is distinguishable from the serpentine. The major serpentine areas are represented on the imagery in a brown color, indicative of its scrubby vegetation; an area mapped as serpentine (Jenkins, 1966; Taliaferro and Solari, 1948) appeared to have a denser vegetation not characteristic of serpentine. When the area was field checked, it was found that this second area was covered with oak-woodland and grassland. Rock outcrops, sampled in the area, were found to be metavolcanic greestones with plagioclase phenocrysts. The area was apparently mismapped by Taliaferro and Solari (1948). Other maps continued the error.

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FIGURES

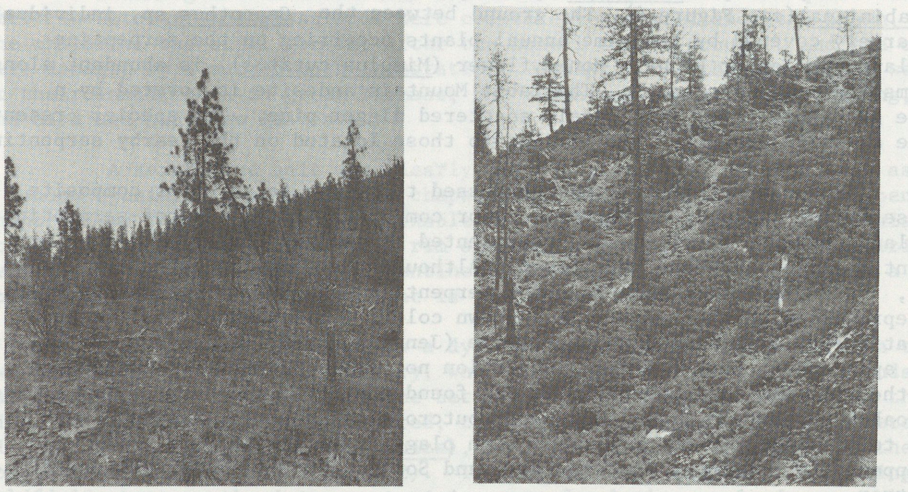

Figure 1. Vegetation on ultramafic rock types at lower elevations (approximately 500m) at the southwest Oregon study area. The left photograph illustrates an open pine grassland developed on serpentine soils while the photograph on the right illustrates a dense sclerophyll shrub layer beneath scattered pines on largely unserpentinized peridotite.

Figure 2. Goldfields (Lasenthia californica) mixed with grasses (foreground) occurring on serpentine soils at the Jasper Ridge Study area. In the background, a grassland consisting predominantly of introduced species is growing on non-serpentinized soils.

Figure 3. Vegetation on metavolcanic soils at the Sierra Nevada foothills study area. The vegetation is an oak-woodland and grassland complex.

Figure 4. Vegetation on serpentine soils (foreground) at the Sierra Nevada foothills study area. The vegetation consists largely of scattered *Ceanothus* sp., digger pine (*Pinus sabiniana*), and annual forbs abd grasses.

TABLES

Table I. Spectral characteristics of the Daedalus DEI-1260 scanner.

Configuration A

Channel #	Bandwidth
- *	0.38 - 0.42um
1	0.42 - 0.45um
2	0.45 - 0.50um
3	0.50 - 0.55um
4	0.55 - 0.60um
5	0.60 - 0.65um
6	0.65 - 0.69um
7	0.70 - 0.79um
8	0.80 - 0.89um
9	0.90 - 1.10um
10	2.05 - 2.35um

Imagery used for:
Southwest Oregon 11Sept 1981
Jasper Ridge 16Oct 1981

*not recorded

Configuration B

Channel #	Bandwidth
1	0.42 - 0.45
2**	0.45 - 0.52
3**	0.52 - 0.60
4	0.60 - 0.62
5**	0.63 - 0.69
6	0.68 - 0.75
7**	0.76 - 0.90
8	0.91 - 1.05
9**	1.55 - 1.75
10**	2.08 - 2.35
11**	10.40 - 12.50

Imagery used for:
Jasper Ridge and Sierra Foothills
23April 1982

**these channels approximate the characteristics of the Thematic Mapper sensor on Landsat 4.

Table I
serpentin
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Table II. Stepwise discriminant analysis classification matrices for serpentine and non-serpentine grasslands on Jasper Ridge for the two image dates.

OCTOBER

Channels selected: 9,4

	% Correct	Observations	
		Serpentine	non-serpentine
Serpentine	77.3%	34	10
non-serpentine	83.1%	10	49
Total	80.6%	44	59

APRIL

Channel selected: 5

	% Correct	Observations	
		Serpentine	non-serpentine
Serpentine	100.0%	35	0
non-serpentine	100.0%	0	55
Total	100.0%	35	55

ABSTRACT

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APPLICATIONS OF REMOTE SENSING TO
GEOBOTANICAL PROSPECTING FOR NON-RENEWABLE RESOURCES

by

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ABSTRACT

Remote detection of geobotanical anomalies is a promising means of mineral exploration. Airborne sensors are able to detect geobotanical stress which is usually manifested by increased reflectance in the visible portion of the spectrum. The change in reflection is caused by a decrease in chlorophyll content which induces chlorosis. The Landsat system is better suited for detecting overall plant density or biomass changes that relate to zones of mineralization.

INTRODUCTION

The heavy demand for and concomitant depletion of the world's non-renewable resources has forced geologists to undertake mineral exploration in areas of difficult access and poor bedrock exposure. Remote sensing is now playing an important role in contributing to exploration programs in these areas. One of the principal causes of poor bedrock exposure is vegetation. Since over two thirds of the world's surface is moderately to heavily vegetated and since most of the future mineral resources will come from these vegetated areas (Raines and Canney, 1980), the study of how changes in surface vegetation manifest changes in subsurface geology is an important prospecting tool. This field is known as geobotany and has been used as a prospecting guide for centuries. When the exploration target is inaccessible, when large areas must be analyzed rapidly, or when geobotanical anomalies are too subtle to be detected with the naked eye, remote sensing techniques can be employed.

Remote sensing of vegetation anomalies may be related to two kinds of geobotanical phenomena : 1) the presence of certain indicator plant species whose growth is restricted to or absent from certain definable geologic units or 2) a change in the physical state of a species distributed over a large area including both the geologic target and the background. Many indicator plants have been identified as useful for mineral prospecting (Carlisle and Cleveland, 1958 ; Cannon 1960 and 1971 ; NASA, 1968 ; Brooks, 1972, and Rose et al, 1979) and many studies have documented changes in the physical state of vegetation such as gigantism, stunting, dwarfing, chlorosis, and mottling (Yost and Wenderoth, 1971 ; Brooks, 1972; Reynolds et. al., 1973 ; Foy et al, 1978).

This paper will review some of the work that has been done on remote detection of geobotanical anomalies. The order of this presentation does not necessarily correspond to the order in which the work has been carried out, but it does provide a framework within which to view the problem : 1) Lab and greenhouse experiments measuring the reflectance of particular plant species stressed by various heavy metals ; 2) field measurements of reflectance and reflected radiance of vegetation growing in situ in various mineralized zones ; 3) Airborne multispectral scanner measurements of various vegetation types growing in situ on various types of ore deposits ; 4) and Landsat satellite studies.

A typical reflected radiance curve of vegetation is shown in Figure 1. The relatively low reflected radiance in the visible part of the spectrum (430-700 nm) is due to strong absorption by chlorophyll centered in two bands at 500 and 690 nm. For a detailed discussion of the visible and near infrared reflectance properties of vegetation, the reader is referred to Knipling (1970). The narrow absorption band centered at 760 nm is due to absorption by oxygen in the atmosphere ; and the absorption bands centered at 720, 820 and 940 nm are due to absorption by water vapor in the atmosphere. While Figure 1 ends at 1000 nm, the near infrared reflected radiance stays high out to about 1300 nm but then starts to fall off due to the presence of water in vegetation.

LAB AND GREENHOUSE STUDIES

Early greenhouse experiments were reported by Press and Norman (1972) who grew bean plants in a nutrient medium spiked with either Pb or Zn. They noted a distinct increase in the reflectance of stressed plants in the 550 nm region of the spectrum but little or no change in the near infrared region (700-990nm) The changes were more pronounced with Pb than Zn and were interpreted as a chlorophyll deficiency in the leaves which reduces the absorption of visible radiation.

Horler et al. (1980 a and 1980 b) undertook greenhouse experiments with pea, sunflower, and soybean plants whose nutrient solutions were spiked with Cd, Cu, Pb or Zn. For the pea plants, they noted a progressive increase in leaf reflectance in the visible wavelengths (475, 550 and 660 nm) and a progressive decrease at near infrared wavelengths (850, 1600 and 2200 nm). These wavelenghts conform to the wavebands in Landsat-D's thematic mapper. Horler et al. note that their results in the visible part of the spectrum are consistent with a decrease in chlorophyll concentration in the stressed leaves, whereas the near IR results support a change in leaf structure. Zn treated soybeans behave similarly to the peas in the infrared, but the soybeans showed a decreased reflectance in the visible (660 nm), while Cu treatment of sunflower showed little effect.

Chang and Collins (1980) have studied the toxic effects of a variety of heavy metals on greenhouse grown varieties of sorghum and mustard. They noted a strong correlation of increased reflected radiance in the visible (550-760 nm) and decreased total chlorophyll in the leaves of plants grown in the presence of Cu, Zn and Ni. First and second derivative spectra of Chang and Collins' data lead them to propose that the long wavelength end of both the 500 and 690 nm chlorophyll absorption bands shifts about 10 to 40 nm toward the shorter wavelengths when the plants suffer heavy metal stress. However, Horler et al. (1980 a and 1980 b) report no shift in absorption spectra. Chang and Collins (1980) also note a small decrease in the near infrared reflectance spectra and report that subtle spectral differences in the 400-500 nm spectral region may be related to an increase in chlorophyll a/b ratio. Horler et al. (1980 b) report decreased chlorophyll a/b ratios in Cd and Cu treatments of pea plants and no change with Pb and Zn, but they conclude that such changes are less reliable indications of heavy metal stress than a decrease in chlorophyll concentration. However, they maintain that their results are not universal and may be reversed.

Schwaller et al. (1981) studied the effects of heavy metal stress on the leaf reflectance properties of sugar maple seedlings. The seedlings were collected in an anomalous copper zone in Michigan's Keweenaw Peninsula and grown in the lab for about 150 days during which time they were treated with varying amounts of Cu and Mn. Across the whole visible and near IR spectrum (475- 1650nm) Schwaller et al. observed increased reflectance for the Cu treated leaves ; but only at 660 and 700 nm do the Mn treated plants show increased reflectance. They did not observe any decrease in reflectance at any wavelength for any of the treated plants. Schwaller et al. note that near infrared leaf reflectance (1300-2500 nm) is controlled in large part by the amount of liquid water in the leaf (Tucker, 1980) ; and relate differences between their work and that of Horler et al. (1980 b) in the near infrared region to lab conditions under which the plants were grown. This is a very significant finding for practical exploration work. Over the large area of an exploration program, it is reasonable to expect that even a farily uniformly distributed species may be growing under very different soil moisture conditions. If this results in varying amounts of water in the leaf or needle structure, then the near infrared spectrum may be responding to these conditions, not heavy metal stress.

The clear indication of the laboratory and greenhouse experiments is that heavy metal stressed plants show increased reflected radiance in the visible portion of the spectrum. This results from chlorosis of the vegetation which is induced by a deficiency of chlorophyll pigment (Elvidge and Lyon, 1982). The results in the near infrared region are variable ; and since they may be only secondarily related to heavy metal stress, they are less reliable.

GROUND BASED FIELD STUDIES

A number of reflectance measurements have been undertaken on natural vegetation growing in the field on various mineral deposits. Notable among the earlier studies are those of Yost and Wenderoth (1971), Howard et al. (1971), and Press (1974). These investigators studied red spruce, fir balsam, ponderosa pine, and cork oad growing in various kinds of ore deposits including porphyry Cu-Mo, vein Cu, and vein Pb-Zn ; and they generally found higher reflectance values in the visible part of the spectrum for the trees growing on mineralized ground. The results in the near infrared part of the spectrum are variable with some workers reporting increased reflectance and others reporting decreased reflectance.

Horler et al. (1980 b) undertook field studies of oak vegetation at a Cu-As mine and found a positive correlation of Cu and As in the soil with reflectance at 660 nm. They also noted that there was no correlation between leaf reflectance and Cu content of the leaves or between soil and leaf Cu content. Horler et al. speculate that the reflectance effects of heavy metal stress are included by interactions between Cu and the tree roots not Cu in the leaves. A similar lack of correlation between the reflectance properties of lodgepole pine needles and metal content of the vegetation and soil was observed by this author in an experiment at Heddleston, Montana (Birnie and Hutton, 1976).

While Horler et al.(1980 b) feel that the change in reflectance properties of the leaves correlates best with total chlorophyll content, Howard et al. (1971) suggest that the increase in reflectance from mineralized vegetation is a function of vegetation density (Ponderosa pine), not changes within the needles. This suggestion is based on the field measurements involving whole branches which showed increased responses over the lab measurements of the needles alone. This indicates one of the significant changes encountered when reflectance measurements are moved from the lab to the field. Depending on the area over which reflectance measurements are integrated, the reflectance properties of more than just the vegetation are measured. To the extent that the undercover is darker than the vegetation, a response from the vegetation as a result of hevay metal stress may be masked. On the other hand, plant density or total biomass may be a useful indication of heavy metal stress.

The field measurements support the laboratory studies indicating that increased reflectance in the visible part of the spectrum generally results from heavy metal stress and that changes in the near infrared part of the spectrum are variable and less reliable.

AIRBORNE MULTISPECTRAL SCANNER STUDIES

To exploit the clear spectral response, particularly in the visible of vegetation to heavy metal stress, airborne multispectral scanners of the type developed by Chiu and Collins (1978) or used by NASA (Milton, 1981) must be used. The lab and field studies described earlier have limited areal coverage and are difficult to conduct where there is poor access ; they are, therefore, unsuitable for a mineral exploration program. Airborne scanners permit rapid coverage of large areas with high spatial resolution (pixels about 20 m on a side) and high spectral resolution (channels as small as 1.4 nm for the Chiu and Collins instrument). Experiments reported by Birnie and Hutton (1976), Birnie and Dykstra (1978), Collins et al. (1977 and 1978), Collins and Chiu (1979), and Birnie and Francica (1981), have used the Chiu and Collins multispectral scanner and found correlations between the spectral data and vegetation growing in mineralized areas. This author and his coworkers report increased reflected radiance values in the visible part of the spectrum for lodgepole pine (670 nm) and douglas fir (560 nm) growing on a porphyry copper deposit. While Collins and his coworkers report a spectral shift of 10-20 nm of the chlorophyll absorption edge at about 700-750 nm in a conifer forest.

The increased reflected radiance in the visible reported by this author and his coworkers is consistent with heavey metal induced chlorosis. However, these changes may also be related to total plant density or biomass. The spectral shift seen by Collins and his coworkers is probably related to a decrease in chlorophyll content of the vegetation since, as reproted by Elvige and Lyon (1982), a decrease in the chlorophyll content increases the reflectance on the edge of the chlorophyll A absorption band (centered at 675 nm) and produces an apparent shift of the absorption edge.

Milton (1981) used band ratios of NASA's 24 channel scanner to map plant species in the East Tintic Mountains, Utah. She created a band ratio image of both visible and near infrared values where each of the three primary colors corresponded to one of the three major plant communities in the area. The areas indicated on the image to contain a paucity of vegetation also correlated with zones of hydrothermal alteration. Schwaller and Tkach (1980) used aerial photographic techniques to detect premature leaf senescence in an area of Cu mineralization but warned that they also detected premature senescence outside the mineralized zone.

On the basis of the limited airborne multispectral scanner work done to date, it appears that the visible region (<750 nm) is the most promising for detecting geobotanical stress related to chlorosis. However, overall plant density determinations require measurements in the near infrared.

LANDSAT STUDIES

The Landsat satellite lacks the high spatial and spectral resolution of the land based and airborne studies ; nevertheless, it is possible to detect geobotanical anomalies from space. Lyon (1975) used a number of Landsat band ratios, of which B7/B4 was best, to discriminate a juniper and pine geobotanical anomaly associated with a skarn molybdenum deposit. Bolviken et al. (1977) detected stands of Cu stressed vegetation on enhanced color ratio images of Landsat digital data : and Lefevre (1982) used Landsat B7/B6 and B7/B5 ratios to detect low vegetation that correlated with geochemical anomalies of As.

This author and his coworkers (Stone, 1982 ; Stone et al., 1982) have used Landsat digital data to map potential mineralized zones to the southeast of the Caraiba Mining District, Bahia State Brazil. The Cu-Ni mineralization in this district is associated with mafic and ultramafic rocks intruded into Precambrian metasediments. The ultramafic units weather in this semi-arid environment into dark brown clay rich soils that contrast significantly with the light toned quartz rich soils developed onthe surrounding metamorphic rocks. Metamorphic terranes are particularly difficult to map using remote sensing techniques because the lithologic boundaries are more gradational and less distinct than other terranes (Abrams, 1980). Geobotanical techniques are particularly useful if they produce distinct boundaries. Low, bushy and succulent plants predominate the Brasilian study area ; and Lewis (1966) noted a strong geobotanical preference of certain plants to either the clay rich soils derived from the mafic rocks or the sandy soils of the metamorphic rocks. The total biomass growing on the mafic soils is also greater (Putzer, 1976).

Numerous investigators have applied various vegetation indices for the purpose of biomass determination (for example Tucker, 1979) ; these indeces exploit the fact that solar radiance in the visible red band (B5) is strongly absorbed by chlorophyll, whereas the near infrared radiance is strongly reflected. After testing a number of vegetation indices, it was determined that the indices that merely examine the difference between the near infrared and visible bands (for example, the DVI of Richardson and Wiegand, 1977 where DVI = 2. 4B7-B5 (Fig. 2) did not accurately reflect the fact that the mafic rock units were more densely vegetated. Since in this semi-arid region the vegetation cover is generally not complete,there is a considerable amount of soil integrated into each pixel ; and the soils derived from the felsic rocks are brighter than those of the mafic rocks. The data presented by Rowan et al. (1974) (Fig. 3) indicate that felsic rocks have greater B7-B5 values. The low vegetation density over the gneissic units allows more soil to show through, and the soils derived from these felsic rocks have high "apparent" vegetation indices relative to the mafic derived soils.

When a standard soil brightness index is applied to the data (for example SBI of Dauth and Thomas (1976) where SBI = 0.433B4+0.632B5+0.506B6+0.264B7 (Fig. 4) the darkness of the mafic soils is clearly manifest. Therefore, when different soils occur under a vegetation canopy, a simple difference biomass indicator must be normalized to account for soil brightness. The vegetation index of Tucker (1979) (VI =(B7-B5)/(B7+B5)) does this and results in an index that shows a strong correlation of increased biomass and mafic rocks (Fig. 5).

The overall index can be improved in this case where dark soils occur on units with high vegetation density by ratioing the vegetation and soil brightness indices (VI/SBI (Fig. 6)). The inverse correlation of the soil brightness and vegetation indices produces a striking separation of mafic and gneissic units.

In many remote sensing studies, naturally occurring vegetation may be a problem because it masks the spectral response of the earth materials (Siegal and Goetz,

1977) ; but in this case, a procedure is developed where the vegetation and soil indexes combine in a consistent way to produce an index that is not compromised by significant variations of either. A similar two-tiered approach using combinations of Landsat band ratios has been used by Raines et al. (1978) to bring out the effects of vegetation (B5/B6) and limonite stained surface (B4/B6) that combine to indicate areas of uranium mineralization.

In general, Landsat will probably not detect very subtle spectral variations due to chlorosis ; however, where a geobotanical anomaly is manifested by a major change in biomass, the Landsat system can be used to map the anomalous areas.

CONCLUSIONS

It should be emphasized that geobotanical remote sensing is no panacea and must be used in conjunction with other exploration techniques. Not all terrains are suitable for geobotanical techniques. For example, the dense Amazon rain forests may not be suitable because nutrients are transferred directly to the plants from the decomposing soil litter (Jordan, 1982). Presumably, therefore, the root structures of these plants are not developed down into the bedrock derived soils, and the plants will not feel the effects of heavy metal stress. In other forests, however, mineral soils play a more important role in nutrient (and presumably toxic metal) storage and transfer (Jordan, 1982). In these latter examples, remote sensing of geobotanical anomalies is very promising.

While work must be done on many different vegetation types under different kinds of heavy metal stress to determine the specific types and causes of the spectral responses, it is clear that remote detection of geobotanical stress is one of the methods that should be used in a mineral exploration program. Spaceborne remote sensors must be designed to detect geobotanical stress, particularly the spectral regions assoicated with chlorophyll absorption in the visible part of the spectrum. Narrow spectral bands (10-50 nm) centered in the visible part of the spectrum around 475, 560 and 660 nm should be most useful. These, of course, correspond to those of the Landsat-D Thematic Mapper. These bands coupled with Landsat-D's near infrared bands centered at 850, 1600 and 2200 nm should be useful for total biomass determinations where a geobotanical anomaly is manifest by plant density.

ACKNOWLEDGEMENTS

The work that was done by this author and his colleagues at Dartmouth College was primarily supported by NASA Grants NGS 5014 (airborne multispectral scanner work) and NAG 5-159 (Landsat Brazil Work) and Dartmouth College. The remote sensing facility at Dartmouth College is also partially supported by NASA Cooperative Agreement NCC 5-22 in collaboration with NASA's Goddard Institute for Space Studies (GISS) in New York City. The author has benefitted from the close collaboration of DR. STEPHEN UNGAR and his colleagues at GISS. The major portion of the Brasilian work was accomplished as a Masters Thesis by THOMAS A. STONE at Dartmouth College.

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FIGURE CAPTIONS

Figure 1 : A generalized reflected radiance spectrum of Douglas fir trees.

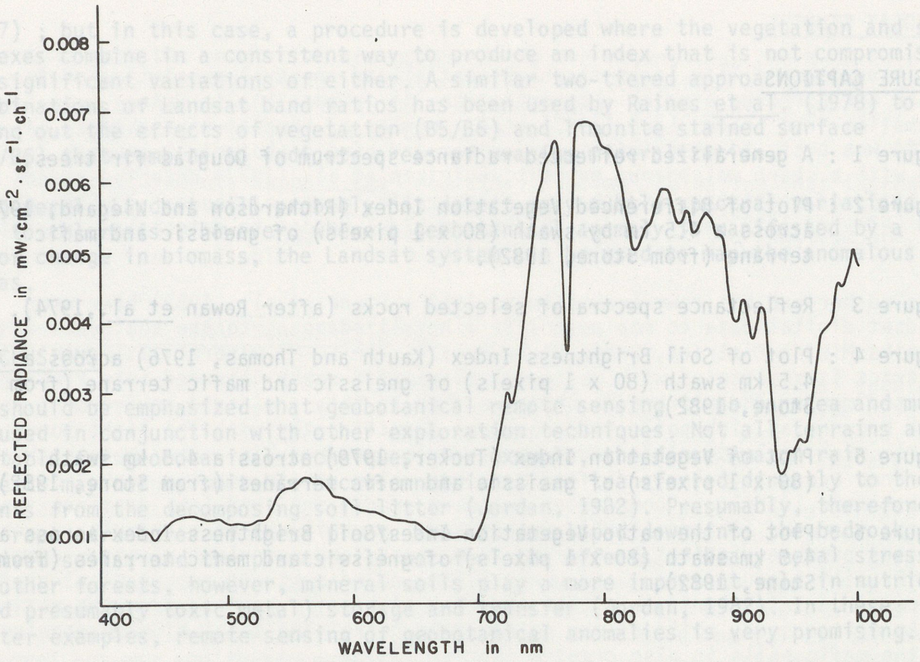
Figure 2 : Plot of Differenced Vegetation Index (Richardson and Wiegand, 1977) across a 4.5 km by swath (80 x 1 pixels) of gneissic and mafic terrane (from Stone, 1982).

Figure 3 : Reflectance spectra of selected rocks (after Rowan et al.,1974).

Figure 4 : Plot of Soil Brightness Index (Kauth and Thomas, 1976) across a 4.5 km swath (80 x 1 pixels) of gneissic and mafic terrane (from Stone, 1982).

Figure 5 : Plot of Vegetation Index (Tucker, 1979) across a 4.5 km swath (80 x 1 pixels) of gneissic and mafic terranes (from Stone, 1982).

Figure 6 : Plot of the ratio Vegetation Indes/Soil Brightness Index across a 4.5 km swath (80 x 1 pixels) of gneissic and mafic terranes (from Stone, 1982).


REFLECTED RADIANCE in mW cm^{-2} sr^{-1} ch^{-1}
0.008
0.007
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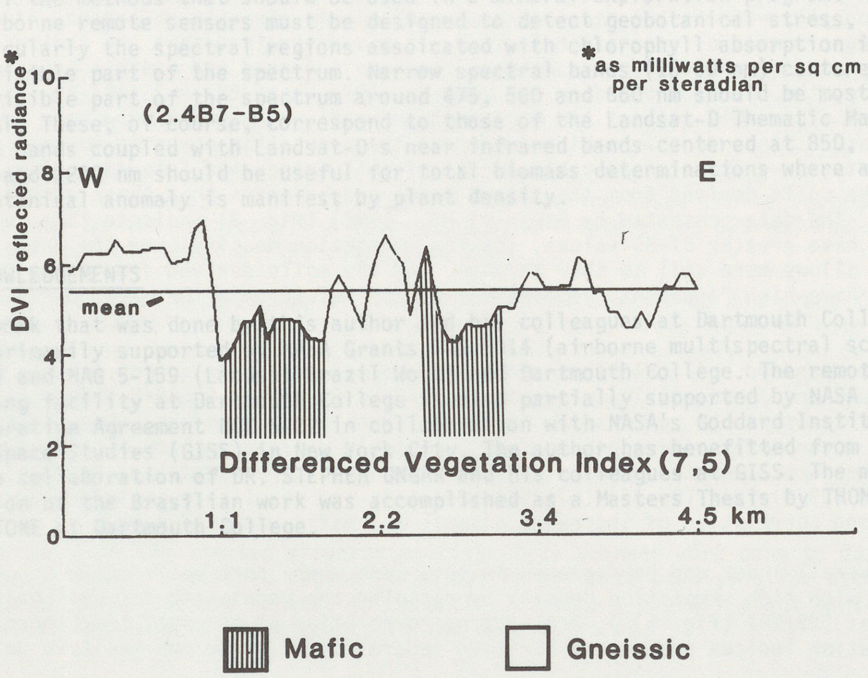
400
500
600
700
800
900
1000
WAVELENGTH in nm

FIG. 1


DVI reflected radiance*
10
8
6
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2
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(2.4B7-B5)
* as milliwatts per sq cm per steradian
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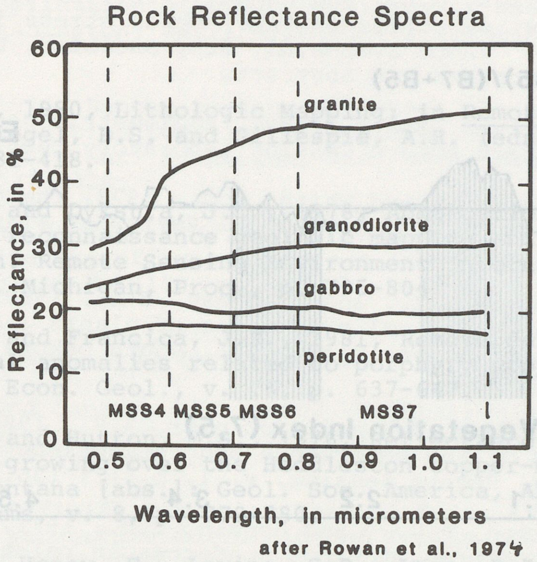
▥ Mafic
☐ Gneissic

FIG. 2



after Rowan et al., 1974

FIG. 3

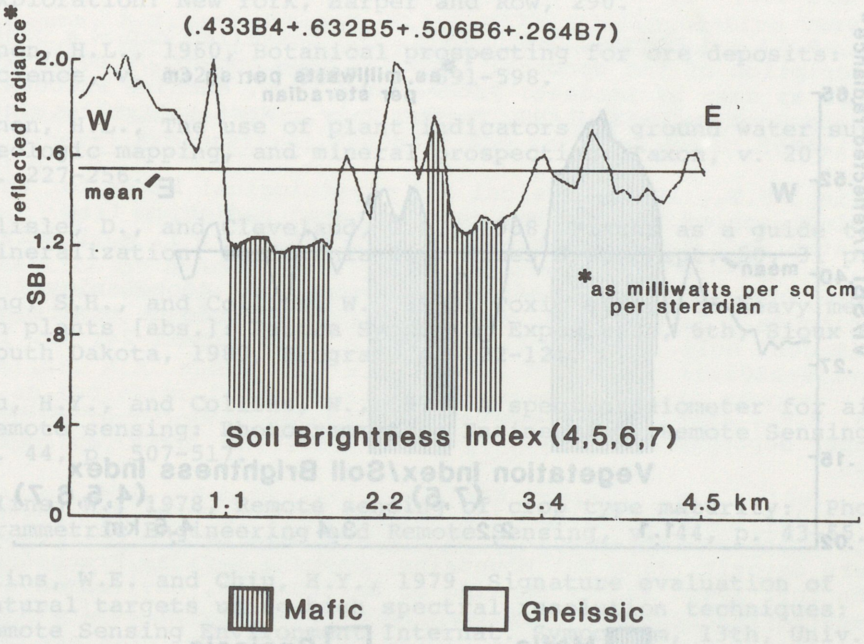


FIG. 4

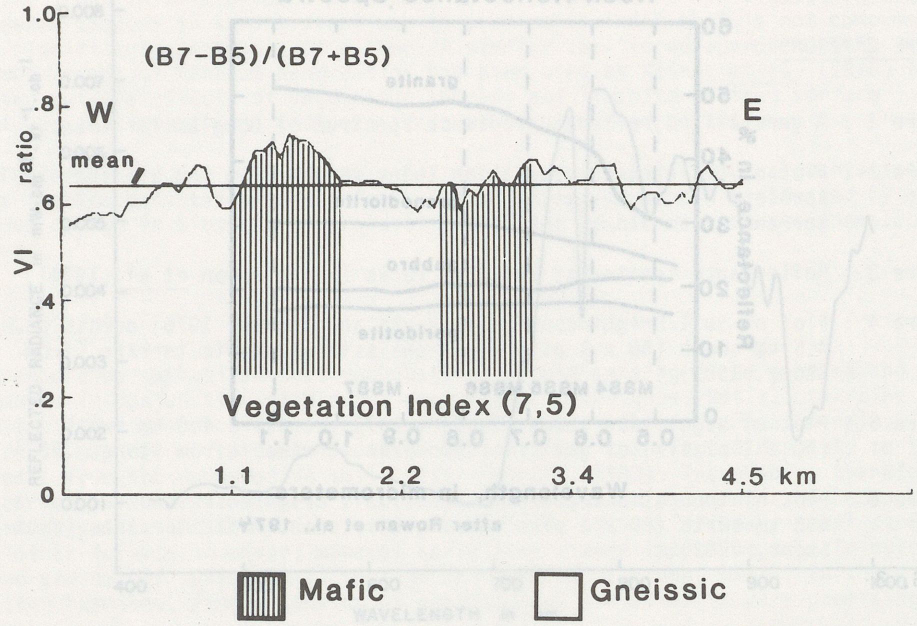


FIG. 5

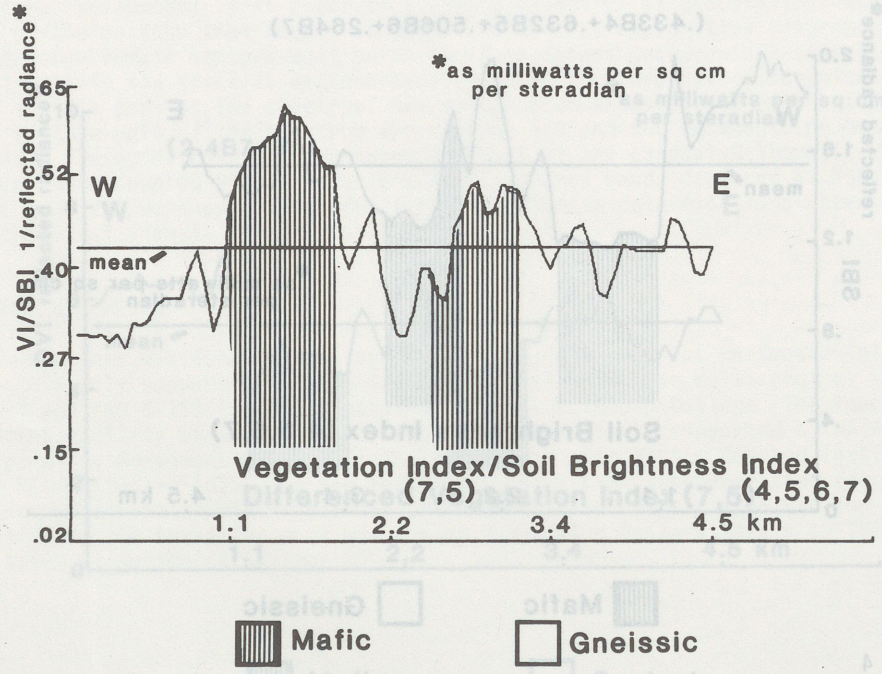


FIG. 6

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GLOBAL SATELLITE REMOTE SENSING FOR ENERGY, MINERALS AND OTHER RESOURCES

by

FREDERICK B. HENDERSON III, PH D., PRESIDENT
THE GEOSAT COMMITTEE, USA

Summary and Introduction

Civil satellite remote sensing systems developed by the U.S., France, Japan, and perhaps others will produce global digital and film data during the 1980's which will provide geological information valuable to the development of non-renewable energy/mineral and renewable resources. Economically feasible global coverage will depend largely upon the development of existing or new cooperative regional ground receiving stations to acquire, process, distribute and archive these data from cooperative satellite producing governments. At present, this development will depend upon the upgrading of 12 or more Landsat 1-3 ground receiving stations to the capacity required to receive and process higher data rate LANDSAT 4/TM data, SPOT data, and Japanese ERS and other satellite data and/or the development of one or more addition regional cooperative station to cover the rest of the world. (See Figure 1) Global access to these data will depend upon cooperation between the ground receiving station countries and satellite producing countries operating under the international "Open Skies" policy (mutual accessibility and availability of data on an equitable basis).

The Landsat System

Systematic global civilian satellite remote sensing was introduced with the U.S. LANDSAT system in 1972. Designed primarily for agriculture, hydrology and land use planning, LANDSAT has demonstrated the geologic value of synoptic perspective, global coverage and increased geological mapping efficiency from space to the energy, mining and engineering industries.

The synoptic perspective has enabled geologists to see large-scale geological features not obvious previously through airborne or ground level geological mapping programs. It has also allowed the geologist to integrate large regional areas geologically in one data base system which, in the past, had to be mosaiced from smaller mapping programs.

The global coverage of satellite data allows an internally consistent digital data set to be created from systems such as LANDSAT, SPOT, and proposed Japanese ERS satellite systems. By the use of the computer, these digital data bases can then be enhanced for optimal geological interpretation and information, digitally merged with one another for mutual enhancement and merged with geographic, magnetic, gravity, geochemical and other digital data bases.

Finally, the increased efficiency in geological mapping stems from the ability to use global satellite data coverage for large scale regional mapping, which in turn allows for the more efficient and effective use of higher-cost airborne and surface ground mapping, and geophysical and geochemical surveys. This will lead to more rapid indication of site-selective areas for specific examination and eventual drilling and testing.

Satellite Remote Sensing for Energy and Mineral Resources

The international industrial geological community is represented by The Geosat Committee, which was created in 1976 to demonstrate the potential benefit of Landsat and future geologically-oriented remote sensing systems. Geological satellite remote sensing capabilities to be added to the current Landsat systems and data base during the 1980's include fixed and pointable digital stereoscopic coverage, increased spatial resolution to 10 meters IFOV (instantaneous field of view), rock/oil sensitive spectral bands in the short wave and thermal infrared portions of the electromagnetic spectrum, and Synthetic Aperture Radar (SAR). Because of increased digital data rates associated with these improvements to the Landsat-type satellite remote sensing systems, adequate ground segment systems for digital data acquisition, processing, archiving, and distribution must be upgraded to handle the data and provide for the growing user market which will develop from the availability of these new data and the geological and other data derived therefrom.

These improved satellite remote sensing capabilities have been studied and are demonstrated by the joint Geosat-NASA Test Case Program, which has made extensive remote sensing studies over three porphyry copper, two uranium, and three oil and gas deposits in the U.S. from 1977 through 1982. These studies have utilized various remote sensing techniques provided by NASA and the Jet Propulsion Lab who flew them over these sites of known geology provided by The Geosat Committee. The site geologic, geophysical, and geochemical information was provided by several Geosat companies. Studies of these systems have been compared, and, in some cases, integrated for maximum geological information. Technique comparisons and geological assessment of these remote sensing capabilities have been jointly studied by geologists from NASA, Jet Propulsion Lab, the U.S. Geological Survey, and from several participating Geosat Committee companies. This multi-million dollar program and its study will be published in early 1983 and will be available through NASA, the AAPG, and The Geosat Committee.

New Satellite Systems for the 1980's

Several global satellite systems to be developed during the 1980's will provide added geological capabilities to the growing Landsat digital data base. The U.S. LANDSAT D was successfully launched and thus became LANDSAT 4 on July 16, 1982. After NASA evaluation, this system will provide both multispectral scanner (MSS) and Thematic Mapper (TM) scanner data, which will improve both the spatial and spectral resolution coverage provided by Landsats 1,2, and 3. The Thematic Mapper, in addition to having four bands

(Bands 1-4) in the visible and very near infrared (VNIR) in the region 0.4 - 1.1 microns, will provide two new shortwave infrared (SWIR) bands which are of considerable value to the geological community. Band 5 (1.6 micron) and Band 6 (2.2 micron) will help correctly identify many geologically important soils and rocks which contain clays, carbonates, phosphates, sulfates, etc. in their mineralogical composition. This will be in addition to the iron oxide-dominated mineralogical and lithological differentiation provided for by the MSS and TM bands. TM Bands 1-6 will also provide improved spatial resolution of 30 meters IFOV. TM Band 7 will provide 120 meters IFOV resolution in the thermal IR region of 10.4 - 12.5 microns.

The French SPOT system, to be launched in 1984, will provide higher spatial resolution and crosstrack stereo capabilities to be added to the global satellite data base initiated by the Landsat program. SPOT will have three bands in the visible/very near infrared (VNIR) range comparable to the MSS and TM Bands 1-4 at a resolution of 20 meters IFOV. In addition, SPOT will provide one panchromatic band in the range 0.51 - 0.73 microns at 10 meters IFOV resolution. Through its dual-pointing optical system, the SPOT satellite will provide selected, programmable crosstrack stereo capability. This stereo capability will provide data over any one given location from different orbits of a minimum of from two or more days apart.

Japan will launch two remote sensing satellites which will provide data of value to the geological community. The Marine Observation Satellite (MOS), planned by the National Space Development Agency (NASDA) is scheduled for launch in 1985. In addition to several oceanographic-oriented bands from its VIR (visible and thermal radiometer) at low spatial resolution (900 - 2700 meters), MOS-1 will also provide four bands in the range 0.51 - 1.1 microns from the MESSR (Multispectral Electronic Self-Scanning Radiometer) at 50 meters IFOV resolution. Earth Resources Satellite (ERS-1), planned for 1987, will be devoted primarily to geological observations. The specific band selection of the ERS-1 satellite is in its final decision-making stage this year, but will be developed around the following sensor types: a) Synthetic Aperture Radar (SAR), probably L-band, with 20-25 meters IFOV resolution; b) bands in the visible/very near infrared and shortwave infrared at about 30 meters IFOV resolution; one or more thermal IR bands at lower spatial resolution. The ERS-1 satellite may also provide a form of stereoscopic coverage.

Film data will be available through the U.S. Large Format Camera and the ESA Metric Camera, both of which will be shuttle launched in the early to middle 1980's. These cameras can provide excellent high resolution (to 10 meters or better) visible and very near infrared film data; however, neither camera program has been funded to provide global coverage as yet.

In several other countries, other film, radar, and multispectral scanning and/or solid state radiometers are proposed, all of which could provide useful geological information. These include the propsed radar satellites; ERS-1 of the European Space Agnecy (ESA) and Canada's RADARSAT. Presumably, these satellites will provide L-band or other Synthetic Aperture Radar data in the general range of 20-30 meter IFOV resolution. In Germany, a high-resolution, multispectral visible/very near infrared solid state radiometer system (MOMS) will be flown in 1983 as part of a shuttle experiment on board a shuttle platform called SPAS.

The Soviet Union, India, and China are planning other remote sensing satellite devices, which may provide usable geological data. However, at present it is not clear whether these data will be available to the general global community nor to what extent they will provide geologically useful data.

Conclusion

It is strongly believed by those who will provide these satellite systems and their ground receiving stations, as well as those in the geological exploration community, who, through The Geosat Committee and elsewhere, have attempted to evaluate the future potential of these satellite systems, that they will in fact provide potentially invaluable data during the '80's. Very useful global geological information can be extracted from these data for the better geologic mapping and understanding of our energy and mineral resources. In areas such as Latin America, where this information can be hard to obtain at present, the development and the availability of this satellite derived data will be of great potential value.

Because of the high cost of obtaining, archiving, and processing data from these future systems and because of the high potential value to future exploration for global non-renewable resources, the successful use of these systems will depend in large measure on international cooperation in developing compatible and complementary space systems and in the exchange of data under the "Open Skies" policy. Of great importance is the fact that these programs all depend on cooperative data sharing, archiving, and global distribution through upgraded existing and planned ground receiving stations in the Americas as well as the rest of the world. Failure to provide upgraded regional ground receiving stations throughout the world may lead to limited access to these data for all.

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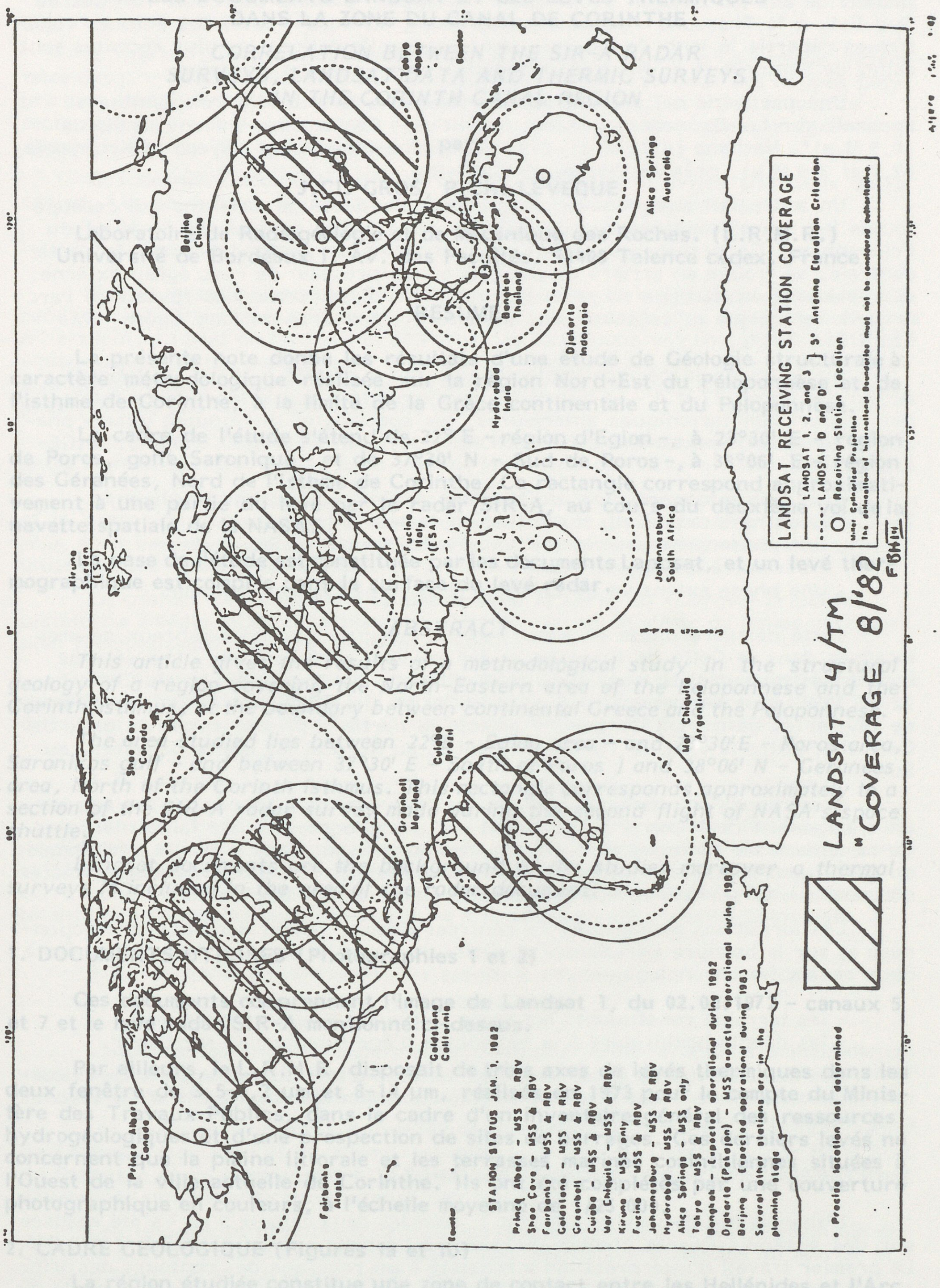

FIGURE 1

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