PROCEEDINGS: Twenty-Sixth Workshop on geothermal Reservoir Engineering
Stanford University, Stanford, California, January 29-30, 2001
SGP-TR-168

COST-EFFECTIVE VEGETATION ANOMALY MAPPING FOR GEOTHERMAL EXPLORATION

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ABSTRACT

Vegetation anomalies are sometimes found over hydrothermal convection systems, where they form because of mineralization, anomalous soil gas, heat, and/or other abnormal conditions. These anomalies are often difficult to delineate without expensive biogeochemical or hyperspectral surveys. This study uses inexpensive Landsat Thematic Mapper (TM) data to delineate vegetation anomalies potentially related to a hydrothermal convection system. Past work by the authors has shown that vegetation anomalies can be affected by seasonality and that plant stress signals tend to increase toward the end of the growing season. Therefore, inexpensive multi-temporal TM data were analyzed to determine if anomalies could be mapped based upon this assumption. Two data sets were acquired in early and late summer 1986 for this purpose. These data were processed to determine the amount of vegetation change over this period, the logic being that the areas showing the greatest change would be those stressed beyond normal seasonal expectations. To accomplish this, the TM data were (1) georectifed and coregistered, (2) processed to remove haze, (3) used to produce vegetation indices, and then (4) used to determine the relative change in vegetation through time. The results clearly delineated several areas showing change beyond what one would expect from normal seasonal variation. One of the anomalies was near the Bonnett Geothermal Power Plant at Sulphurdale, Utah. Field checking several other areas, mapped as anomalies, revealed over-grazing by cattle to be the probable causal agent. Although this method makes no distinction between causal agents of plant stress, its low cost, ease of use, and usefulness in limiting the extent of targets, especially when used with ancillary exploration data, can make it useful for reconnaissance exploration programs.

INTRODUCTION

Geobotanical anomalies have been related to hydrothermal convection systems. Detection of these anomalies can be useful for geothermal exploration, especially when used with other traditional methods, by adding another degree of confidence where correlation exists. This paper describes a simple and inexpensive technique that facilitates detection of anomalous change in vegetation through time. Some of the detected anomalies may have a relationship with a hydrothermal convection system.

Remote sensing has been utilized to map geobotanical anomalies associated with mineral deposits and hydrothermal convection systems. Additionally, geobotanical and biogeochemical prospecting techniques have been proven useful for mapping geologic substrate and mineral anomalies (Brooks, 1988; Rose et al., 1987). Biogeochemical techniques have also been utilized to prove mineral uptake, including gold, in several species of plants (Erdman et al., 1988; Rose et al., 1987; Erickson et al., 1986). Soil-geochemical, biogeochemical, and vegetal-spectral anomalies have been detected in association with several hydrothermal convection systems in the western U.S. (Klusman et al., 1999; Nash and Wright, 1996; Hinkle, 1995; Hinkle and Erdman, 1995; Hinkle et al., 1995).

As certain elements are toxic to vegetation, their presence in underlying zones of mineralization can, if accessed by the root system, cause stress. The stress manifests itself as morphological and mutational changes to the plant (geobotanical anomalies). These changes can be observed through certain structural and physiological expressions, which may include dwarfism, gigantism, or chlorosis (Brooks, 1983). Dwarfism and gigantism are relatively easy to spot in the field. Chlorosis and other changes at the cellular level, on the other hand, may cause subtle changes not readily apparent to the unaided human eye. Therefore, methods, such as color infrared photography interpretation and spectroscopic analysis, have come into use due to characteristic changes in vegetation spectra as a response to stress (Johnson and Nash, 1998; Nash, 1997; Nash and Wright, 1996; Carter, 1994; Carter, 1993; Curtiss and Maecher, 1991; Brooks, 1983; Lourim and Buxton, 1988; Singhroy et al., 1986).

The most noticeable effects are well-documented spectral shifts along the red edge and overall increases in albedo (Baret et al., 1990; Lourim and Buxton, 1988; Singhroy et al., 1986; Collins et al., 1983). Shifts in the red edge (chlorophyll absorption edge) are the result of either chlorophyll loss (blue shift), or chloroplast damage (red shift) (Curtiss and Maecher, 1991). Stressed vegetation has also been detected using spectral band ratios, particularly the 694 nm/760 nm ratio, and by an increased reflectance in the 400-700 nm range, which may be the most consistent indicator (Carter, 1994).

In general, for effective detection of vegetation anomalies when using visible and near infrared data, the data must be of resolution high enough to allow the isolation of subtle spectral features such as the shifts along the red edge. At the present time, data from hyperspectral instruments, that collect spectra in the aforementioned region of the electromagnetic spectrum at high spectral resolution, are not widely available. Airborne data are most useful and can be acquired at spectral and spatial resolutions amenable to accurate vegetation analysis, however this data is expensive, and difficult to acquire and process in relation to medium spectral resolution data. A new hyperspectral instrument, Hyperion, was recently launched aboard a satellite by NASA. This instrument should provide useful data in the near future, but data access is limited.

Medium spectral resolution data are generated by several satellite-borne instruments and can be acquired easily and at low cost. However, their resolution is not amenable to precision vegetation anomaly mapping. This data is, however, useful for general vegetation mapping and processing techniques are relatively simple. This paper will detail how these data can be used to locate potential vegetation anomalies, for very low cost, in regional reconnaissance exploration for geothermal resources. The area of study was the Cove Fort-Sulphurdale thermal anomaly, Utah, on which the Utah Municipal Power Agency operates the 5- megawatt Bonnett geothermal power plant.

GEOLOGIC AND GEOGRAPHIC SETTING

The Cove Fort-Sulphurdale thermal anomaly is located along the northwestern flank of the Tushar Mountains and the southwestern flank of the Pavant Range in central Utah. Tertiary volcanic rocks, erupted between about 19 and 30 m.y.a., dominate the geology of this area. These were derived from two volcanic centers -- the Marysvale volcanic belt to the east and the Basin and Range to the west (Ross and Moore, 1985).

The system’s heat is generated from deep circulation. It lies in the tectonically extensional Great Basin and is structurally controlled by thrust faults developed during the Sevier Orogeny and both low- and high-angle normal faults which have developed more recently under current extensional tectonic conditions. A landslide block overlays the system forming an almost impermeable cap, therefore, few surficial expressions of this system exist.

Topography of the area ranges from nearly flat at the valley edge, to dissected foothills on the landslide-block overlying the footwall of the range-front fault. The elevation ranges from about 1840 m-1960 m and the climate is temperate. Temperatures can dip below 0^o F. in the winter and climb to over 100^oF in midsummer at the extremes. Area rainfall for 1986, the year the imagery used in this study were acquired, was 9.36 inches, although it may have been somewhat higher over part of the thermal anomaly due to the orographic effect of the aforementioned mountains.

Vegetation in the study area consists primarily of pinyon-juniper forest along with associated communities of big sagebrush with rubber rabbit brush appearing in disturbed areas. Bitter brush and gamble’s oak are also found on some slopes, and grasses are abundant in areas where the pinyon-juniper forests have been chained to improve forage for cattle.

OBJECTIVES

The objectives of this study were two-fold. The first was to determine if low-cost Landsat Thematic Mapper (TM) data could be used to detect vegetation anomalies caused by stress that may be related to hydrothermal convection systems. This was to be accomplished by determining the amount of seasonal change in the vegetation cover over the study area, the logic being that stressed vegetation will show more change seasonally then healthy vegetation. This logic is derived from work done by Nash (1998) on vegetation stress detection using a high-resolution field spectrometer in Dixie Valley, Nevada. In the Dixie Valley study, stressed vegetation, in the early summer, showed less sign of stress then it did in the late summer, after additional stressors, such as heat and a reduction in available water, had come into play. However, it must be noted that no controlled laboratory experiments have been done by the author to corroborate this hypothesis at the time of this writing.

The second objective was to track and report the costs-benefits of the study. This report is intended to give industry enough information (1) to repeat this methodology and incorporate it into their exploration plans if wanted, and (2) to give them a reasonable estimation of the costs involved.

DATA

Data used for this study consisted of two Landsat Thematic Mapper (TM) scenes, one acquired on June 15, 1986 and the other on September 3, 1986. These data, although several years old, were considered to be adequate assuming the effects of a hydrothermal system on vegetation should be fairly consistent through the human time scale. Each TM scene covers an area of about 34,000 km^2. Spatial and spectral resolutions are given in Table 1. Landsat 4 and 5 TM data, 10 years old or older, can be purchased from the USGS EROS Data Center archive for $425.00 per scene plus a $5.00 handling fee. This archive could be accessed at http://edcsns17.cr.usgs.gov/EarthExplorer/ at the time of this writing. However, the USGS has indicated that http://earthexplorer.usgs.gov/ will be active by publication time. Orders can be placed online via the Internet and the data can be obtained on CD-ROM, 8-track tape, or by electronic transfer. Recently acquired Landsat 7 Enhanced TM (ETM) data can be obtained for $600.00 per scene from the same site. As the archive data used in this study were over 10 years old, the total cost was $860.00. As this study used two images, the raw data cost per km^2 was a very reasonable $0.02529, or $0.01265 per km^2 per single image, if considering usage of the entire image area. This makes TM data very cost effective for regional exploration.

DATA PROCESSING

Preprocessing

Before any preprocessing can be done, the TM data must be downloaded onto a local hard-drive. The data is generally stored in a band-sequential (BSQ) format with each band consisting of an individual data file of *i* columns by *j* rows. The columns and rows must generally be known to import the data into an image processing software package, although some packages will retrieve this information from data headers, especially if using Landsat 7 data. In this case the import will be automatic. If automatic import is not facilitated, then the column and row information can be found in ancillary text files that accompany the data files. This is generally a simple procedure. In this study, the column and row information was found in the header text files, which were viewed with a text editor.

Before any interpretation, the TM data were prepared using both preprocessing and image enhancement processing techniques. When working with spectral data from satellite or airborne instruments, it is advisable to do atmospheric corrections or haze reductions. This is not as critical for medium

Table 1. TM spectral and spatial resolution.

LandSat 4-5 Resolution	Spectral - micrometers	Spatial - meters
Band 1	0.45-0.52	28.5
Band 2	0.52-0.60	28.5
Band 3	0.63-0.69	28.5
Band 4	0.76-0.90	28.5
Band 5	1.55-1.75	28.5
Band 6	10.40-12.50	120
Band 7	2.08-2.35	28.5

resolution TM data as it is for hyperspectral data, but this processing will generally facilitate better data interpretation. Therefore, the first TM preprocessing step was a dark object subtraction. This method, though not as rigorous as some, is simple, fast, and will generally produce good results. This method is detailed by Chavez (1988) and has been incorporated into several image processing software packages.

The second and final preprocessing step was georectification. In this process ground control points are collected from GPS data, maps, or other projected data sets. Digital orthoquads were used for ground control collection in this study. The ground control points were applied to the TM data sets for rectification and projection into UTM coordinates. This allows the later co-registration of derived data and other geological, geochemical, and geophysical data sets for spatial and correlation analysis.

Vegetation Enhancement

The first TM processing step was vegetation enhancement. The normalized difference vegetation index (NDVI) transform, and other vegetation indices as described by Jensen (1986), reduce the bands used as input to a single output band that is useful for assessing biomass, productivity, leaf area, and/or the percent vegetation ground cover. Vegetation indices, at their most basic level, enhance the visibility of vegetation in the output image. The two co-registered preprocessed data sets were digitally manipulated to create the NDVI, which is described mathematically as

$$NDVI = \left(\frac{TM4 - TM3}{TM4 + TM3} \right) \qquad (1)$$

where TM3 and TM4 refer to the specific TM band numbers as shown in Table 1 above. An output example can be seen in Figure 1.

Change Detection

The two NDVI images were then used for change detection -- which is described mathematically as

$$\Delta X_{ijk} = BV_{ijk}(1) - BV_{ijk}(2) + c \qquad (2)$$

where
ΔX_{ijk} = output change pixel value;
$BV_{ijk}(1)$ = June, 1986 NDVI pixel brightness value;

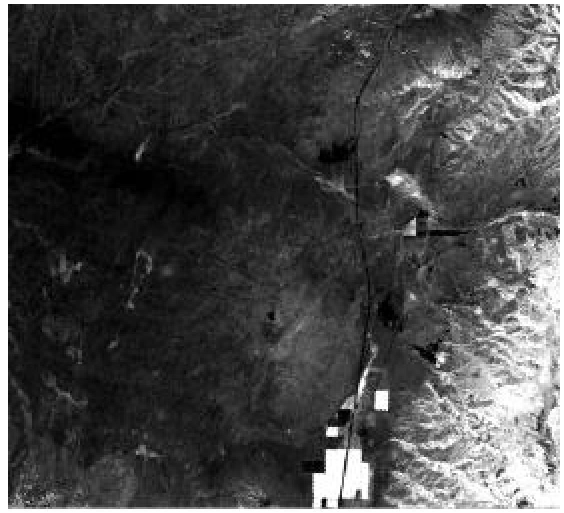

Figure 1. June NDVI image. Vegetation appears bright. Brightness is dependent upon vegetation density, vigor, and type.

$BV_{ijk}(2)$ = September, 1986 NDVI pixel brightness value;
c = an empirically derived constant to eliminate negative values;
i = NDVI image, line 1…n;
j = NDVI image, column 1…n;
k = a single NDVI image.

This process is conceptually explained as the difference between the early summer NDVI and the late summer NDVI, which results in a single band image on which areas with little change appear dark and those areas with significant change appear light. Most image processing software packages have a band math option that allows the analyst to easily accomplish this operation.

A problem can occur using this method where the value of $BV_{ijk}(2)$ is greater then the value of $BV_{ijk}(1)$; therefore, the analyst must use care in interpretation. This problem produces a negative outcome, which is scaled by c to a relatively low BV on the output change image. For some types of analyses this might pose a problem. However, this problem is trivial when considered for this study where the affected areas were farmlands, on which crop-cover had either increased in density and greenness through the growing season or harvest had occurred, and obviously not anomalies. One would generally expect the TM *BV*s for vegetation cover in natural areas to decrease in the study area over this same time period due to the effects of heat and dryness, and as senescence nears in late summer/early autumn.

DISCUSSION

The change image derived from the two NDVIs can be seen in Figure 2. Upon inspection one can readily see a number of areas that are considerably brighter then surrounding areas. These were the targets of interest. The targets were outlined with vector GIS polygons that were transferred to USGS digital raster graphic 1:24,000 7.5-minute quadrangles, which were printed to facilitate field checking.

Several mapped targets (labeled in Figure 2) were visually inspected during a field visit to the study area. Obvious factors in vegetation change were the early senescence of cheat grass and effects from farms. Bright areas on Figure 2 with cheat grass cover or farms (bright areas not labeled) were identified but not inspected as no useful information could be derived. Changes in areas A-G were related to grasses, other then cheat grass, with a generally minor sagebrush component. These grasses were approaching senescence and were suffering from obvious damage from cattle overgrazing. The latter is believed to be the primary causal agent of change in these areas. Areas H and I were believed to be affected by a combination of anthropogenic activity, grasses going into senescence, grazing, and an unknown factor. The unknown factor could be effects from the thermal anomaly, which is known to exist under or in close approximation to these areas.

GIS was then used to facilitate further interpretation. Faults (Steven and Morris, 1981) were overlain on the georeferenced change image to determine if any anomalies were correlative (Figure 3). It can be observed, when comparing Figure 3 to Figure 1, that all areas field checked, with the exception of area A, correlated with one or more mapped faults. This would indicate that, although other factors were observed and believed to be the cause of most of the anomalies, these areas should not be completely ignored in an exploration effort. Elimination of these targets should rely on the lack of correlation with other pertinent exploration data.

However, based on the information created by and used in this study, the best targets were believed to be areas H and I. Area I had anomalous change showing over the most diverse group of vegetation types.

COSTS-BENEFITS

Costs-Benefits are provided to allow members of industry to decide if this methodology would be useful in their exploration programs.

Costs

Costs are estimated from what are believed to be conservative estimates based on the

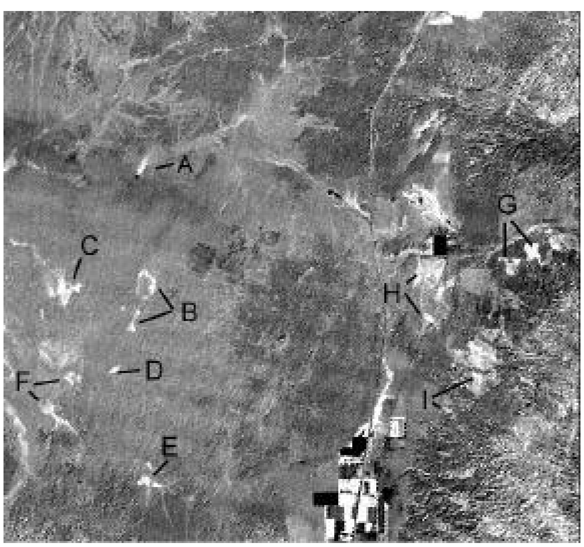

Figure 2. Vegetation temporal change image with field-checked anomalies labeled.

Figure 3. Vegetation temporal change image with faults overlay.

methodology outlined in this paper. It is assumed that a professional geoscientist, with some experience in remote sensing, would do the data processing, analysis, fieldwork, and data interpretation.

The costs of replicating this study would include (1) TM data purchase, (2) TM data preprocessing, processing, and analysis, (3) field work, (4) digitization of faults in a GIS format, and (5) labor. Labor is considered at $60.00/hr. It must be noted here that the entire area covered by the TM imagery was not processed or field checked in this study. Only the area over and adjacent to the known hydrothermal convection system was analyzed. This area consisted of 18,141 km^2. The estimated cost breakdown is as follows:

Purchases:
TM (2 scenes) $860.00
USGS 1:24000 7.5 minute quads (8) $36.00

Data Preprocessing:
Data download/conversion (2 hours) $120.00
Atmospheric Correction – dark object subtraction (1 hour) $60.00
Georectification (8 hours) $480.00

Data Processing:
NDVI creation (2 hours) $120.00
Change image creation (1 hour)............... $60.00
Initial Interpretation (1 hour) $60.00
Field Map Preparation (2 hours) $120.00
Fault vector data capture* (8 hours) $480.00
Final Interpretation (2 hours) $120.00

Field Work:
Transportation (400 miles @ 0.33/mile). $132.00
Motel (one night) $55.00
Per diem (2days @ $35.00/day) $70.00
Salary (16 hours) $960.00...................... $960.00

Total Project Cost $3733.00

*This data may be available digitally at lower cost.

Some of these costs, such as travel and labor, will vary from project to project. The listed costs should, however, give the reader enough information to make a reasonable estimation of cost when this methodology is applied to any given project. If the entire area of the TM scene is considered, increases in cost would reflect primarily fieldwork and the digitization of faults to cover the larger area. The costs of processing and interpreting the TM data over a larger are is relatively trivial. It is estimated that processing the entire image would add about 12 hours labor for processing one or two days additional field expenses.

The above costs do not reflect the actual cost for development of the final methodology presented in this paper. Many different processing techniques were tested to determine the most useful methodology for vegetation anomaly mapping related to geothermal exploration in this study.

Benefits

The benefits of using this methodology are many. The first and foremost is that it allows the analyst to easily see and map potential vegetation anomalies, overlay the anomalies on maps for field checking, and determine which anomalies may be related to phenomena that are not apparent in the field, such as hydrothermal convection. Although these types of vegetation anomalies cannot be directly attributed to a causal agent using only the technique described in this paper, the information, when used in concert with other geological, geophysical, hyperspectral, geochemical, and/or biogeochemical data can add a greater degree of certainty to possible exploration targets. Most importantly, it can be used for negligible expense. Using the total cost given above, considering the partial TM scene used in this study, the total cost for this study per km^2 would be only $0.2058. The cost per unit area would decrease if an entire TM scene were analyzed, as described above, even considering the additional field and processing time. This methodology may also be useful in monitoring vegetation change through time as related to geothermal power generation. Vegetation anomalies are often created as production causes fluctuations in reservoir pressure.

Other benefits would be derived from having the TM data on-hand. This data can be further used to (1) map faults/lineaments, (2) map hydrothermal alteration, (3) aid in general geologic mapping, and (4) produce pre-exploration and production base-line environmental data.

CONCLUSIONS

The use of TM derived NDVI data through time can be useful for mapping vegetation anomalies, which may be produced differentially by seasonal stressors. This is based on the hypothesis that plants, stressed early in the summer, will become increasingly stressed relative to plants that are not stressed, as heat and a reduction of moisture are applied through time.

The causal agents of anomalies, that become apparent by differencing two TM NDVI images, may or may not be readily apparent in the field. If not, one can assume that a subsurface factor, such as hydrothermal convection, may be a factor. A lack of a vegetation anomaly, however, should not be considered as an indication that no hydrothermal convection exists as the vegetation over a tightly sealed system may show few if any effects. The uncertainty in the result of this methodology is not as large a problem as it may seem. This method is not meant to stand alone. It is meant as an inexpensive method to produce data that can be used in concert with other traditional and nontraditional exploration methods.

The data used to achieve the results discussed here are readily available and inexpensive. Many image-processing packages are available commercially and even some of the most inexpensive and fundamental image processing software can be used to replicate the methodology discussed here in a timely manner.

The cost of using this methodology is very low. However, benefits are not as great some other remote sensing techniques or other more traditional exploration methods used in geothermal exploration. However, this method can add another degree of confidence, when mapping potential targets during reconnaissance exploration, if positive signals are detected, field checked, and correlated with data derived using other exploration methods. Additionally, TM data can be used for other aspects of exploration and production as an additional benefit.

ACKNOLEDGEMENTS

We would like to thank the DOE Idaho Operations Office, U. S. Department of Energy, for their support of this work, which was done under contract DEFG0700ID13958.

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