ENHANCED LANDSAT THEMATIC MAPPER IMAGERY FOR EXPLORATION GEOLOGY IN THE WHEATON RIVER DISTRICT, SOUTHERN YUKON

Peter von Gaza and J. Ronald Eyton
Department of Geography
University of Alberta
Edmonton, Alberta
T6G 2H4

VON GAZA, P. and EYTON, J.R., 1988. Enhanced Landsat Thematic Mapper imagery for exploration geology in the Wheaton River District, southern Yukon; in Yukon Geology, Vol. 2; Exploration and Geological Services Division, Yukon, Indian and Northen Affairs Canada, p. 99 - 107

ABSTRACT

Digitally enhanced Landsat Thematic Mapper (TM) imagery was evaluated as a mapping aid for the exploration geology in the Wheaton River District of the southern Yukon. Landsat TM data acquired on September 1986 was digitally processed to enhance lineaments and alteration zones. Geological mapping was conducted at a reconnaissance scale of 1:250 000 for a 45 km by 45 km area centered the Wheaton District and at a detailed scale of 1:50 000 for the Mt. Skukum Volcanic Complex. Reconnaissance investigations showed that the TM imagery was valuable for detecting and mapping small scale geological lineaments and for recognizing limonitic rocks. The imagery, however, was not useful for identifying or differentiating lithologic units. A further limitation of the imagery was the loss of information in the shadows created by the extreme topography of the region and the low sun angle present at the time of image acquisition. Detailed field investigations conducted on the Mt. Skukum Volcanic Complex showed that edge enhanced Landsat images were capable of detecting most of the previously mapped faults and fractures, and some dikes. Three unmapped and potentially significant lineaments were mapped using the TM imagery. These new lineaments (Vesuvius-Chieftian Hill, Sulphide Creek, and Rhyolite Creek) are probably deep-seated fractures. Alteration zones, primarily iron oxide rich rocks, were also mapped successfully. Attempts at identifying hydrothermally altered rocks failed. Overall, Landsat TM imagery was found to be a valuable tool for mapping geological lineaments and iron oxide alteration zones at scales between 1:250 000 and 1:50 000.

RÉSUMÉ

On a évalué l'imagerie cartographique thématique Landsat accentuée numériquement, dans le but de faciliter la cartographie en rapport avec l'exploration géologique du district de Wheaton River dans le sud du Yukon. On a traité numériquement les données cartographiques thématiques Landsat (TM) obtenues en septembre 1986, pour accentuer les linéaments et les zones d'altération. On a réalisé la cartographie géologique à une échelle de reconnaissance de 1/250 000, dans une région de 45 kilomètres par 45 kilomètres centrée dans le district de Wheaton, et à une échelle de 1/50 000 pour le complexe volcanique de Mt. Skukum. Les travaux de reconnaissance ont montré que l'imagerie TM était précieuse, lorsqu'il s'agissait de déceler et de cartographier des linéaments géologiques de petite envergure, et d'identifier les roches limonitiques. Toutefois, l'imagerie n'a pu servir à identifier ou à différencier les unités lithologiques. Une autre limitation de l'imagerie était la perte d'information causée par les ombres résultant de la topographie extrêmement prononcée de la région, et du faible angle de la lumière solaire incidente par rapport au sol, au moment de l'acquisition des images. L'exploration détaillée effectuée sur le terrain à l'emplacement du complexe volcanique de Mt. Skukum a montré que les images Landsat à contours accentués permettaient de repérer la plupart des failles et des fractures déjà cartographiées, et quelques dykes. On a cartographié, en employant l'imagerie TM, trois linéaments encore non cartographiés et potentiellement importants. Ces nouveaux linéaments (Vesuvius-Chieftian Hill, Sulphide Creek et Rhyolite Creek) sont probalement des fractures installées en profondeur. On a aussi cartographié avec succès les zones d'altération, surtout composées de roches riches en oxydes de fer. Par contre, on n'a pu identifier les roches qui ont subi une altération hydrothermale. Dans l'ensemble, on a constaté que l'imagerie TM Landsat était un outil précieux pour cartographier les linéaments géologiques et les zones d'altération avec oxydes de fer, à des échelles comprises entre 1/250 000 et 1/50 000.

INTRODUCTION

Landsat Thematic Mapper (TM) imagery was evaluated as an aid for mineral exploration in the Wheaton River District of the southern Yukon during the field season of 1987. This paper briefly describes some commonly used digital image enhancement techniques, and discusses the application of these techniques to the geology of the Wheaton River District. This part of the Yukon was selected as the study area because the overall geology of the region is reasonably well understood, the landscape is not densely vegetated, and the area is currently the focus of intense exploration for potential epithermal gold-silver deposits.

Remote Sensing for Exploration Geology

Satellite remote sensing technology has played an increasingly larger role in the search for mineral resources over the past two decades. Landsat TM images can provide geologists with a synoptic view of the earth's surface in seven spectral bands at a 30 metre resolution. Satellite images have not yet replaced (nor are they likely to in the future) the necessity for field geology, nor have they diminished the role of conventional aerial photographic interpretation in geological mapping and exploration. Landsat imagery combined with all other available exploration methods provides a more effective means for addressing and solving geological problems (Siegal and Gilliespie, 1980).

Research has shown that of the many potential uses of remote sensing imagery for exploration geology, two specific applications are valuable: 1. the mapping of regional and local lineaments, and 2. the detection of hydrothermally altered rocks (Henderson and Rock, 1983; Rowan and Lathram, 1980; Sabins, 1987). Many mining districts and individual ore deposits occur along or near linear trends. These faults and fractures may represent conduits through which hydrothermal fluids migrated, and therefore controlled the distribution of ore deposits. More recently, Sibson (1987) has discussed the importance of the structural control of epithermal mineralization in dilational fault jogs, at macroscopic through regional scales. Modern day exploration geologists spend a considerable amount of time and funds actively seeking and developing techniques for identifying lineaments. The view of extensive areas provided by Landsat is a valuable tool for mapping potential fracture and/or fault patterns, especially in areas where very little is known about the geological environment.

The multispectral characteristics of the Landsat sensing systems provided a means of detecting and mapping altered rocks (primarily limonitic rocks), and the addition of the TM sensor system to the Landsat platform in 1982 considerably improved the potential for detecting hydrothermally altered rocks (Henderson and Rock, 1983). The inclusion of TM band 7 centered at 2.2 um in the electromagnetic spectrum (a region where hydrous minerals have a distinct absorption feature in their spectral curve) theoretically provides the capability for identifying clay minerals associated with hydrothermal alteration (Podwysocki, et al., 1980). This characteristic of band 7 has been used successfully to detect iron oxide free alterations, such as advanced argillic and silicic rocks that are highly leached (Abrams, 1982). The identification of altered rocks, especially hydrothermally altered rocks commonly associated with ore deposits, indicates likely areas for field exploration.

Data

The digital image data used for this study was captured by the TM multispectral scanner onboard the Landsat 4 satellite on September 6, 1986 at approximately 9:30 A.M.. The image was obtained with a sun azimuth of 153 degrees and a sun elevation of 34 degrees. A quarter of a full Landsat scene (a quadrant), with a footprint of approximately 85 km, was obtained from the Canada Centre for Remote Sensing (CCRS) satellite receiving station located at Prince Albert, Saskatchewan. The TM sensing system has a spatial resolution of 30 metres and records seven spectral bands consisting of three visible bands, three near-infrared bands (reflected solar radiation), and one thermal infrared band (emitted terrestrial radiation).

PHYSICAL SETTING

The study area (Fig. 1) lies mostly in the Wheaton River District, on the eastern edge of the Coast Mountains, just north of the British Columbia boundary. The district is approximately 50 km south-southwest of Whitehorse. While the general study area covers a 45 km by 45 km square, the primary focus of this paper is on a 15 km by 15 km subset of the Mt. Skukum area. The topography is moderately rugged, and is described by Cairnes (1912) as an uplifted and deeply dissected peneplain in which the valleys have been greatly modified by Pleistocene glaciation. The major valleys are over 1 km wide and valley slopes rise in excess of 1000 metres to the plateau surfaces. These extensive upland plateaus are undissected and gently rolling.

The vegetation cover is distributed primarily as a function of topography. Spruce, fir, poplar, and pine forests are found in the valleys and on hillsides to an elevation of 1300 metres. Willows are abundant along flood plains, while dwarf birch is plentiful in the higher valleys. Upland plateaus, generally occurring at elevations above the tree line, are characterized by alpine vegetation, including ericaceous shrubs, prostrate willows, and a ground cover of mosses and lichen.

The basic geology described here is confined to the Mt. Skukum Volcanic Complex as it is the focus of the study. The Skukum Volcanic Complex, the northern most extension of the Sloko Volcanic Province found in western British Columbia, is a series of Paleocene-Eocene andesitic and felsic volcanic rocks that have been deposited unconformably on Cretaceous granitic rocks and older metasedimentary rocks of the Yukon Group (Pride, 1986; Smith, 1983; Wheeler, 1961). The complex is highly fractured, is intruded locally by felsic stocks and dikes, and is fault bounded. Iron staining and gossans are prominent; locally, rocks are highly leached and hydrothermally altered. The discovery of the Mt. Skukum gold-silver deposit in 1980 has resulted in considerable exploration activity, focused primarily on locating epithermal gold deposits. The Mt. Skukum deposit is in andesites of the Skukum Complex and consists of low sulphide, high level, gold-silver bearing quartz-calcite veins (McDonald, 1986). Omni Resources Inc. and Skukum Gold Inc. are currently exploring deposits located along Skukum Creek. These deposits are mesothermal, are hosted in granitic basement rocks, and consist of gold-silver bearing rhyolite and andesite dikes, and brecciated quartz veins that have a high sulphide content (Elliot, 1988, pers. comm.). The Skukum Volcanic Complex may be analogous to the setting of epithermal deposits of Silverton, Colorado and is thought to have the potential to yield multiple small tonnage and possibly a few large tonnage, high grade ore deposits (Doherty, 1988, pers. comm.).

DIGITAL IMAGE PROCESSING

Remote sensing strategies for mineral exploration have been steadily moving away from the direct photogeologic interpretation of conventional, unenhanced photography to the analysis of computer manipulated digital imagery (Goetz, 1980). A digital TM image consists of a regularly gridded set of picture elements, or pixels, that represent 30 metre square ground areas. Each pixel contains a numerical record (called Digital Numbers or DNs) of the amount of electromagnetic radiation reflected or emitted from the earth's surface in a particular band. This section of the paper provides a brief

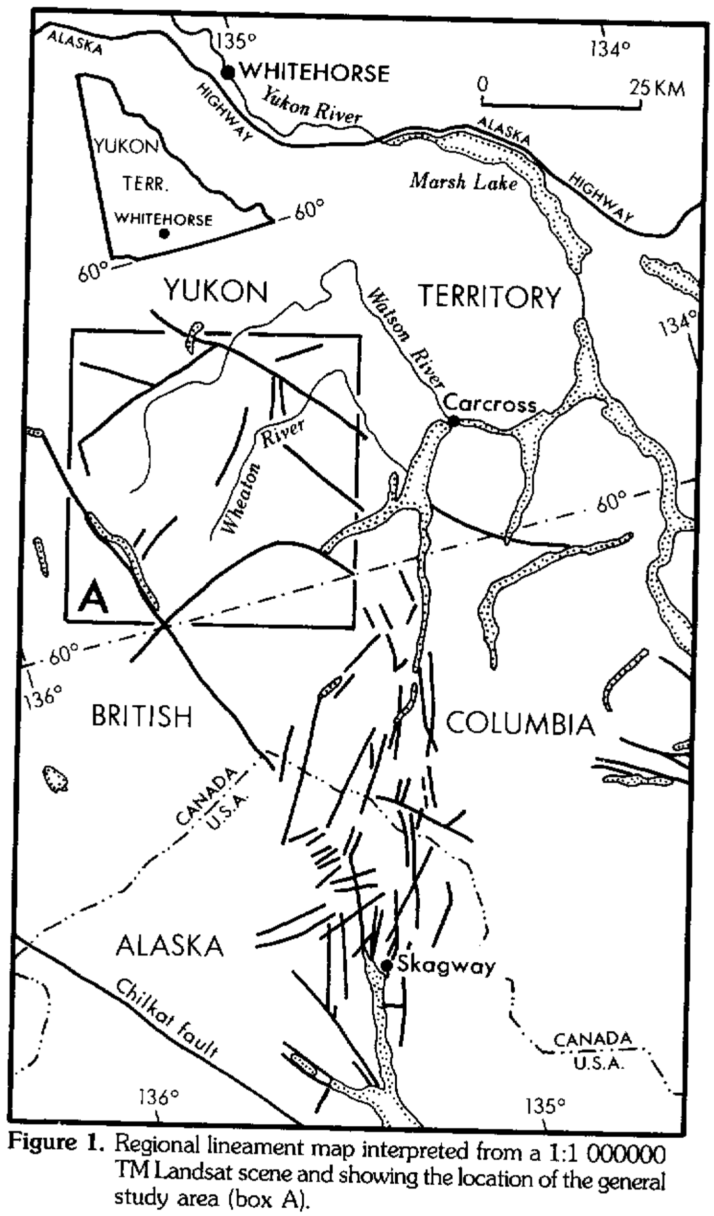


Figure 1. Regional lineament map interpreted from a 1:1 000000 TM Landsat scene and showing the location of the general study area (box A).

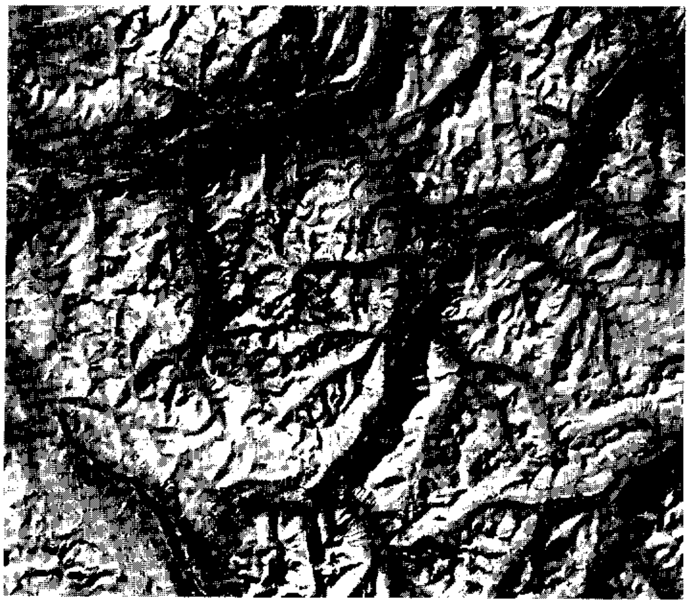


Figure 2. Edge enhanced Landsat TM band 5 image of the general study area.

description of the computer processing techniques used in this study to enhance the TM digital images. A detailed discussion of basic image processing can be found in Schowengerdt (1982), Drury (1987), and Sabins (1987).

The image enhancement techniques used in this study consisted of contrast stretching, spatial frequency filtering, principal components analysis, and band ratioing. Although this paper is restricted to the printing of only black and white photographs, color compositioning techniques are discussed because they are often the end product of the enhancement process. The work was done on a Decision Images image processing system at the University of Alberta, and on a Dipix Aries system operated by the Government of Alberta. Hardcopies of the images were recorded on either a 35 mm Dunn Camera or an 8 x 10 Optronics image writer.

Contrast stretching is a procedure for improving the overall contrast of an image. The raw image will normally have poor contrast when displayed; this is because the image data rarely encompass the full brightness range of the TM sensors. In general a contrast stretch transforms the data to make use of the full range of the output device, resulting in an image that is easier to interpret.

A colour composite is an image produced by simultaneously displaying three bands, with each band assigned one of three additive primary colours (red, green, and blue). This technique for combining bands is valuable because the composite usually displays more information about surface materials than can be found in a single band image. A normal colour composite simulates a natural colour image; it is produced by displaying the visible TM bands 1, 2 and 3 as blue, green, and red respectively. A false colour composite is produced when one or more infrared (IR) bands are combined with one or more visible bands. False colour composites produce colours that are not natural but in many instances provide increased differentiation between surface features because of the addition of the infrared information that is not visible to the human eye.

High-pass spatial frequency filtering is a technique for enhancing tonal boundaries or edges in an image. These edges are important to the geologist as they may represent faults or fractures, or boundaries between geologically significant materials. Tonal boundaries are produced by the juxtaposition of different surface materials, and by the differences in illumination between areas of differing topography. Edge enhanced images are most commonly created by high-pass convolution filtering (Drury, 1985, 1986).

Principal components analysis (PCA) is a statistical method of trans-forming the raw image data to produce new data sets that are uncorrelated. Certain TM image band pairs are often highly correlated and therefore composite images may contain redundant information. PCA produces transformed data, or principal component images, in which all inter-band correlation has been removed. PCA is often used to produce images that are often more interpretable than the original data (see Jensen, 1986, for a thorough discussion of this technique).

Ratio images are generated by dividing the DN of one band by the DN of another band. Certain ratios can be used to enhance the subtle tonal differences between specific cover types while suppressing the effects of illumination (Sabins, 1987). This technique has been extensively used by geologists for enhancing the detectability of altered rocks (Rowen et al., 1974).

REGIONAL ANALYSIS

The Landsat satellite program has proven to be an ideal, cost effective tool for investigating small scale regional structural patterns and for reconnaissance analysis of iron oxide occurrences (Abrams, et al., 1982). Two scales of imagery were used for this part of the study: 1:1 000 000 and 1:250 000. A 1:1 000 000 false colour composite, produced by CCRS, was interpreted for very small scale lineaments. This scale of imagery is generally not useful for reconnaissance studies, but is included in this paper because it helps to place the study area in a regional perspective (Fig. 1). A prominent set of lineaments trending north were visible between the Skagway area in Alaska and Lake Bennett in the Yukon. These lineaments have very strong topographic expression, and likely control the orientation of major lakes, valleys, and ridges. They may represent conjugate fractures related to a compressional environment, bounded on the south by the Chilkat fault and on the north by the Whitehorse Trough.

Digitally enhanced images were produced at a scale of 1:250 000 for the 45 km by 45 km general study area and interpreted as part of a detailed reconnaissance study. A false colour composite (TM bands 5, 4 and 3 assigned red, green, and blue respectively) and a spatially filtered band 5 black and white image (Fig. 2) were used to examine regional lineament patterns and to detect gross areas of iron oxide occurrences. Ground truthing indicated that the images were very useful for detecting limonitic rocks and for mapping regional and local fracture patterns. However, it was not possible to identify rock types or discriminate between different lithologic units. The ubiquitous cover of lichens on virtually all exposed and unaltered rock outcrops, irrespective of rock type, controlled the spectral response in all bands. The extreme topography in the region, and the low sun angle at the time of image acquisition, also complicated interpretation because of the resulting shadows on many northwest facing slopes. In some instances there is a complete loss of image information in the shadows.

Most areas of iron staining and extreme surface alterations were easily detected on the IR false colour composite. This is principally due to the fact that most of these altered areas were devoid of a lichen cover and were spectrally distinct. The majority of the bright areas in Fig. 2 represent limonitic rocks. Areas characterizing by intensely leached rocks had strong spectral responses in all bands, and were easily recognized on the imagery as the brightest reflectors. Field inspection revealed that these leached areas are sometimes characterized by hydrothermal alterations. Alterations in the Mt. Skukum area, on Mt. Vesuvius, and the south face of Mt. Reid are prominent. Generally, limonitic rocks appeared turqoise or pinkish in color and leached rocks appeared bright white on the false colour composite.

The potential fracture map (Fig. 3) represents a conservative interpretation of the regional lineament pattern. Major linear features were easily seen in Fig. 2. The northwest trending fault mapped by Cairnes (1912), along the north side of the Watson River, exhibited a strong topographic expression. A series of linears trending north-northwest were seen in the upper right portion of the image. These features were mapped and named the Tally-Ho Shear Zone by Doherty and Hart (1987, pers. comm.) who used the false colour Landsat image for projecting the trend of the shear zone during field mapping. This feature is a 1-4 km wide, 35 km long zone of sheared greenstones and mylonites (Hart, 1988, pers. comm.). In the bottom right of the image, part of the ring-dike fracture zone around the Bennett Lake Caldron complex is visible. Overall, the image shows that the region is dominated by north to northeast trending

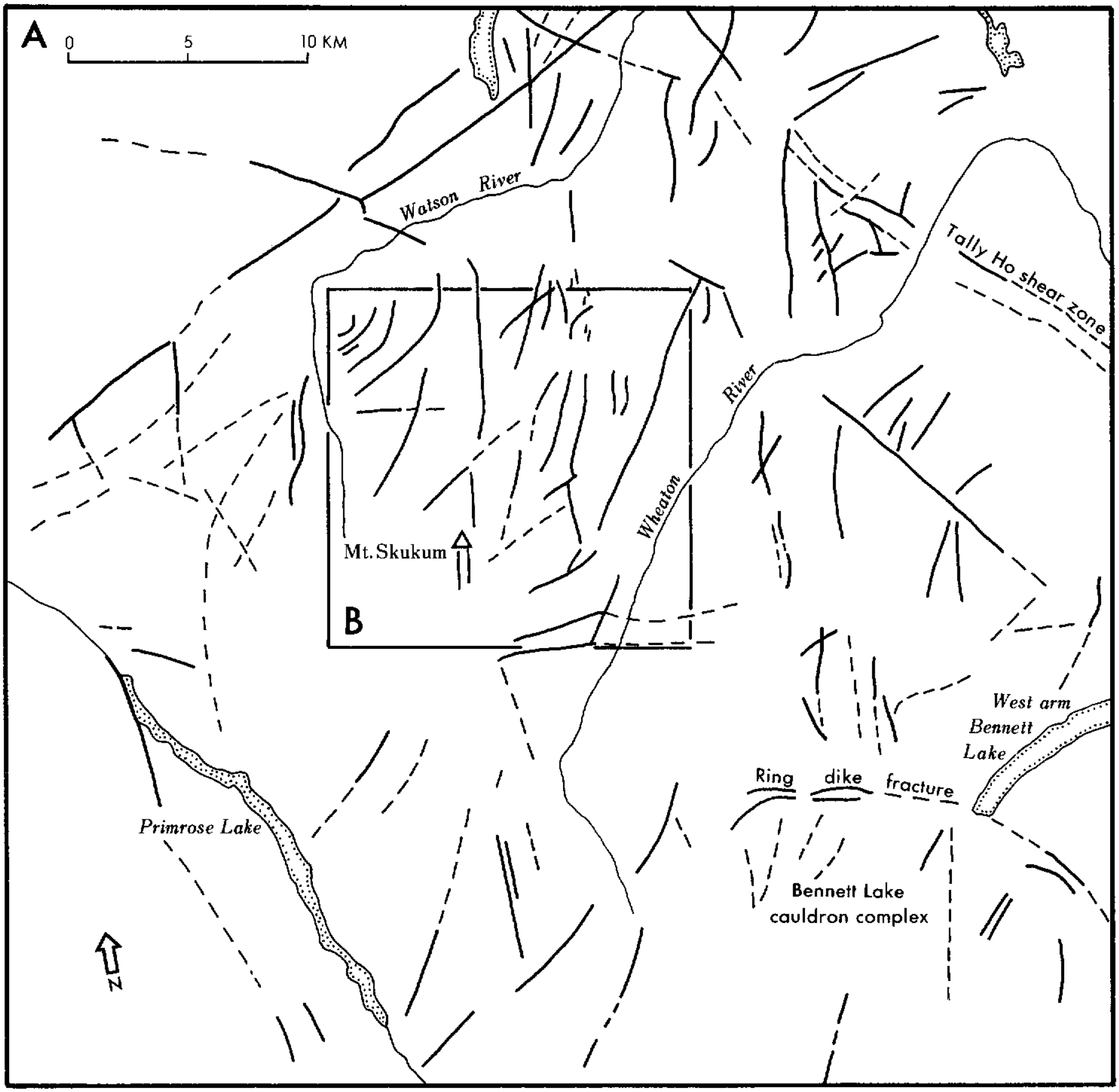


Figure 3. Interpretation of lineaments on 1:250 000 TM imagery centered over the general study area and showing the Mt. Skukum study area (box B) in Fig. 8. Solid lines are distinct lineaments and dashed lines are possible lineaments.

lineaments. These fractures which are often associated with zones of strong surface alteration, may represent areas of possible mineralization, and therefore should be considered for more detailed field investigation.

LOCAL INTERPRETATION

A 15 km by 15 km subset centred over the Mt. Skukum Volcanic Complex was used for mapping altered rocks and fractures at a scale of 1:50 000. The objective of this part of the study was to determine to what degree TM imagery was useful for local, detailed mapping. Image enhancement techniques included black and white contrast stretching (Fig. 4), spatial filtering, normal and IR false colour compositing, band ratioing, and principal components analysis.

Alterations

A series of ratio principal component images and their composites were examined for evidence of spectral response to iron oxide minerals and possible differentiation of hydrothermally altered rocks. The 3/1 ratio image (Fig. 5) proved valuable for isolating and enhancing areas rich in iron oxide minerals. Band 3 detects light in the red portion of the electromagnetic spectrum and is useful for detecting limonitic rock that exhibit a red colouration. The 3/1 ratio removed the confusion that existed in the band 3 image between altered areas and snow (compare Fig. 4c and Fig. 5). Attempts at detecting clays using the 5/7 ratio image as either a single band image or in conjunction with other ratio images to form a colour composite, were not successful. Areas of known argillic alteration in areas dominated by limonitic rocks were used as training samples; intensely altered areas in Sulphide and Rhyolite Creeks were chosen as the specific test sites. Most of the clay alteration was associated with highly leached areas which had very strong spectral responses on

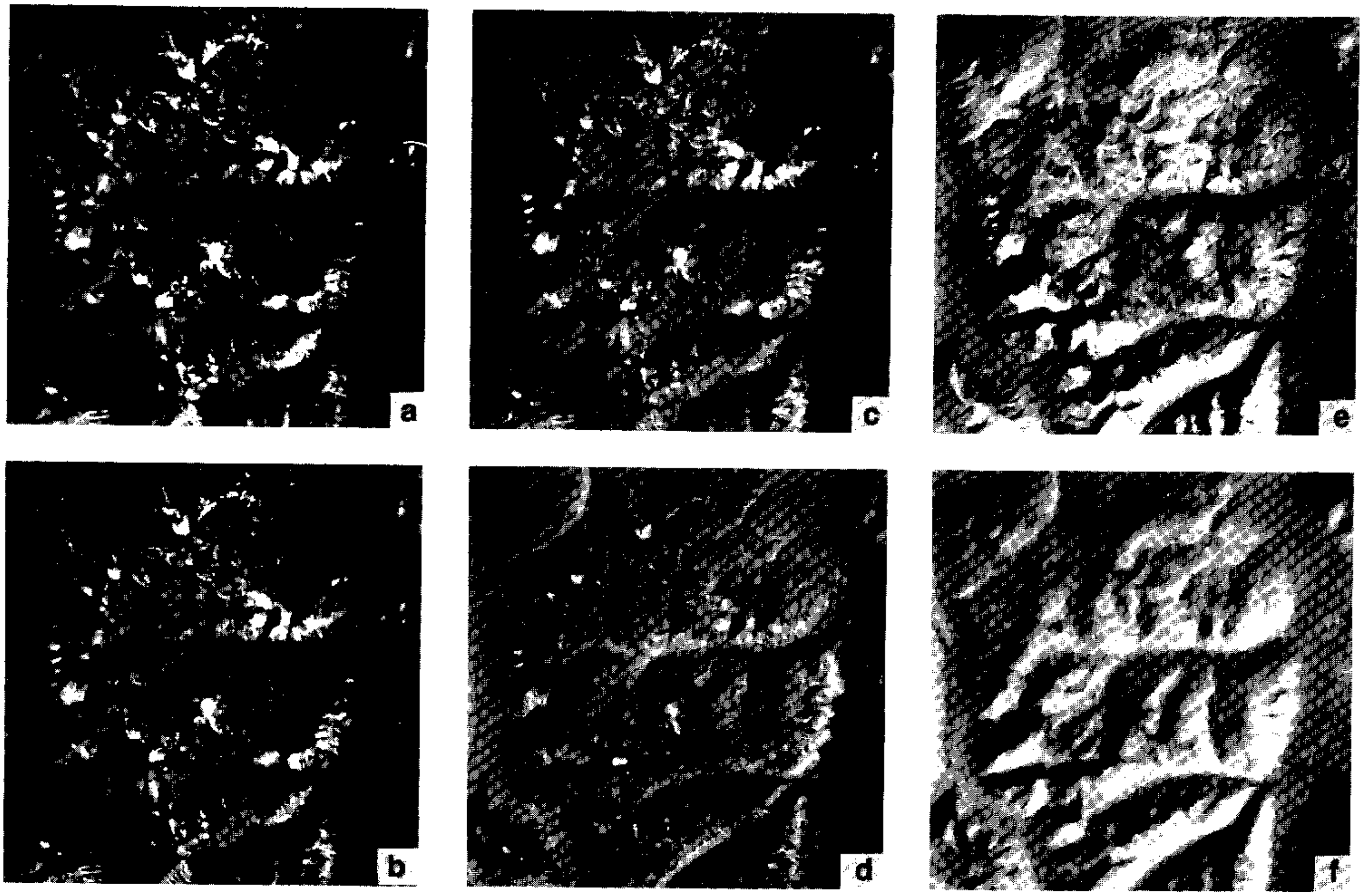


Figure 4. Contrast stretched images of all seven Landsat TM bands. (a) TM1: reflected blue-green light, .45 - .52 um, (b) TM2: reflected green light, .52 .60 um, (c) TM3: reflected red light, .63 - .69 um, (d) TM4: reflected infrared radiation, .76 - .90 um, (e) TM5: reflected infrared radiation, 1.55 - 1.75 um, (f) TM6: emitted thermal infrared radiation, 10.40 - 12.50 um, (g) TM7: reflected infrared radiation, 2.08 2.35 um.

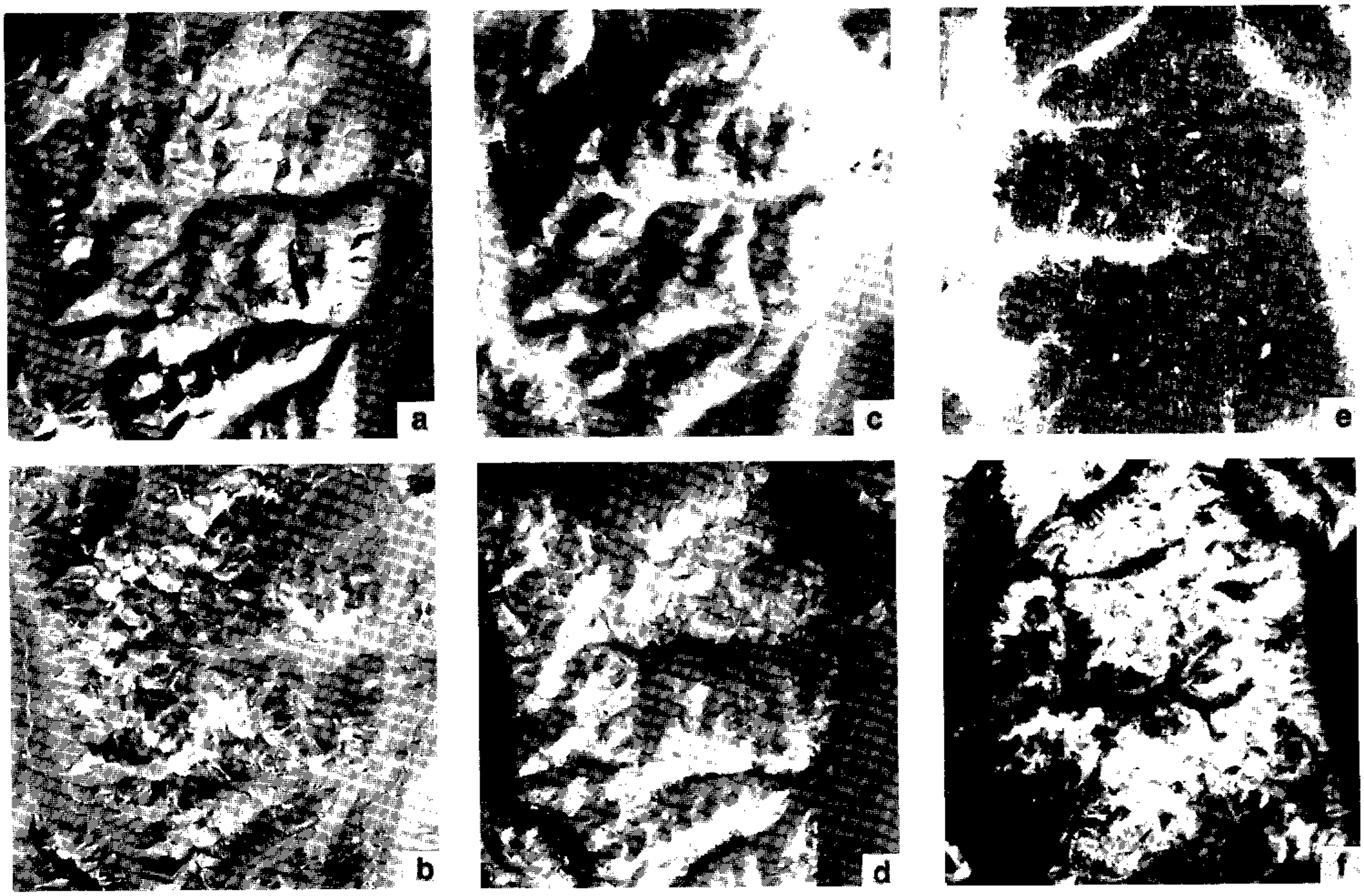
the imagery because of their high albedo. The ability to spectrally detect clays would have aided in the differentiation of hydrothermally altered rocks from weathered bedrock and surface materials containing iron oxide minerals. It is important to realize that these techniques were developed for detecting altered rocks found in desert environments and characterized by sparse vegetation, little weathering, and well defined outcrops typical of the geological environment found in Goldfield, Nevada (Goetz and Ashley, 1979). The application of these techniques to wet, vegetated, and highly weathered environments such as the Yukon, is conjectural.

Inverted principal components analysis (Williams, 1983) was investigated as a possible method for detecting altered rocks. The analysis was undertaken on image data covering areas of known alteration. The resulting seven principal component images are shown in Fig. 6; PC images 1, 3 and 4 were used to created a color composite. These three components were chosen to construct the composite because they exhibited a strong contrast between altered areas and the rest of the image, and the effects of snow were suppressed. The resulting colour composite was dramatic and proved to be extremely useful. All vegetation generally appeared purple, except for lichen covered rocks which were green. Areas of alteration were bright yellow to orange and were very distinct in the image.

The use of a normal colour composite (bands 3, 2, 1) and a false colour composite (bands 5, 4, 3) were found to be generally effective for detecting most of the areas of alteration. In the normal colour composite, areas of iron staining appeared yellow to red, while in the false colour composite they exhibited a turquoise to pink hue. Highly leached areas appeared white in both images. A disadvantage of these images, over the ratio and principal component images, is that much closer examination of the images was required to detect the altered areas; the chance of missing an altered area was greater because these areas did not stand out from the rest of the image.

Lineaments

Local lineaments were identified by examining a spatially filtered band 5 image (Fig. 7) and the false colour composite. Lineaments mapped from both images (Fig. 8) were compared to existing geological maps (1:25 000) compiled by Pride (1985) and checked in the field by one of the authors (von Gaza). Analysis of lineaments



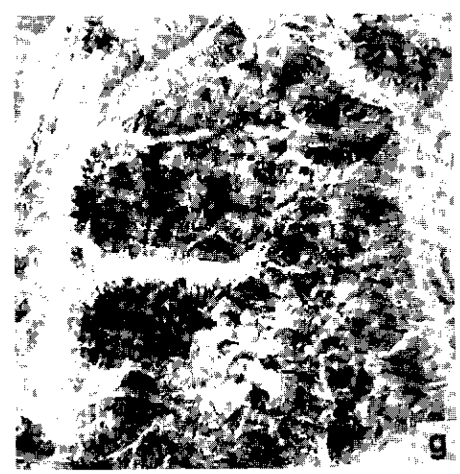


Figure 6. Principal component (PC) images of the Mt. Skukum Volcanic Complex. (a) PC1, (b) PC2, (c) PC3, (d) PC4, (e) PC5, (f) PC6, (g) PC7.

interpreted from the imagery revealed that many previously mapped faults, fractures, and dikes were clearly visible on the imagery. The enhanced imagery also proved useful for detecting linear features that had little topographic expression. Most of these lineaments were detected because of their tonal contrast with the background. A large number of subtle lineaments, primarily fractures and dikes, were mapped north of Butte Creek and in the Main Cirque area north of Mt. Skukum; many were adjacent to local areas of surface alteration. Larger structures, like the Bernie Creek Fault and the fracture along the slopes of Mt. McNeil, were also prominent in the imagery. In the northeast corner of the complex are a distinct series of radial gulleys that exhibited a strong topographic expression. It is the interpretation of the authors that these features may represent block-faults, or slump features, that formed during the collapse of the volcanic complex. Previously unmapped lineaments, some quite significant, were detected on the imagery. These include a series of three north-northwest trending lineaments, all loosely parallel and approximately 15 km in length; these were given the preliminary names of the Vesuvius-Chieftain Hill, the Sulphide Creek and the Rhyolite Creek Lineaments.

The Vesuvius-Chieftain Hill Lineament extends from north of Mt. Vesuvius, across Summit Creek, across Chieftain Hill and joins the Bernie Creek Fault. This lineament was identified primarily because of the vegetation contrast exhibited in the IR bands. The Sulfide Creek lineament also intersects the Bernie Creek Fault and forms a shallow angle to the Vesuvius-Chieftian Hill Lineament. This lineament is expressed in the form of a V-shaped valley along the western margin of Chieftain Hill before becoming part of Sulphide Creek; to the north, the same lineament becomes an incomspicuous depression over Mt. Kopjie and then branches into a series of discontinuous shallow fractures. The Rhyolite Creek Lineament originates at Pyroclastic Cirque, extends through Rhyolite Creek, and then runs parallel to the Sulphide Creek Lineament. The Sulfide and Rhyolite Creek Lineaments are topographic features that were identified because of their conspicuous small scale appearance on the TM imagery. This demonstrates the value of the synoptic view afforded by Landsat; these features would have been difficult to identify from the ground or from large scale aerial photographs. No evidence for faulting was found along any of the three lineaments. Gravity and magnetic aerial surveys conducted for the Mt. Skukum Gold Mining Corporation over these lineaments indicate that they may represent deep-seated fractures (Gossan, 1987, pers. comm.). The association of these fractures with zones of intense alteration indicate areas that are potential exploration targets.

Figure 5. Band ratio (3/1) image of the Mt. Skukum Volcanic Complex. Altered rocks, primarily limonite, have been enhanced and appear bright white.

MISCONCEPTIONS OF REMOTE SENSING

The experience of one author (von Gaza) during the 1987 field season in the Yukon indicated that some individuals have either overestimated the potential value of remote sensing technology or have avoided it because of reports of bad experiences by a few individuals. Remote sensing technology to aid exploration geology in the Yukon has only recently been introduced and therefore is not well understood. There are relatively few users of this technology in the Yukon, and even fewer that have the training and the background for properly applying or making judgments of potential uses.

The approach that some researchers have taken to Landsat image interpretation has resulted in skepticism and disquiet among many scientists to the entire field or remote sensing. This cynicism is primarily related to the interpretation of the images by investigators with little or no photogeological skills. Some critics perceive remote sensing specialists as little more than computer analysts, with inadequate training in the earth sciences. This view grew out of the plethora of lineament studies that inundated scientific journals from the mid- to late seventies (Drury, 1987). During this period almost every conceivable lineament study was attempted and maps saturated with lines, both real and imaginary, were produced in profusion. Donald Wise (1982) wrote of this period, "There have been few fields of geology so marked by uneven quality of collection, digestion and interpretation of the basic data". To many, the term "lineament", when used in the same sentence with "remote sensing", became a dreaded word associated with bad science.

Remote sensing has also been perceived by some as a magic tool that can identify ore deposits or worse still, actual drill sites. This is primarily an educational problem and can be traced to the early days when the justification of the Landsat satellite data products resulted in extravagant and unrealisitic claims of its incredible potential. Orbital satellite imaging systems, it was claimed, were capable of finding ore deposits, oil fields, groundwater, and renewable resources--and all by computer! The ability to directly detect and identify certain surface materials, especially those associated with ore deposits, has always intrigued a large proportion of the geological remote sensing community. To the disappointment of many, two decades of remote sensing has clearly shown that spectral remote sensing, though extremely valuable, has not lived up to its original expectations.

Much of current remote sensing research for exploration geology is entrenched in what is referred to as "spectral-target" remote sensing. Concern and consternation has arisen among some scientists

Figure 7. Edge and contrast enhanced Landsat band 5 image of the Mt. Skukum Volcanic Complex.

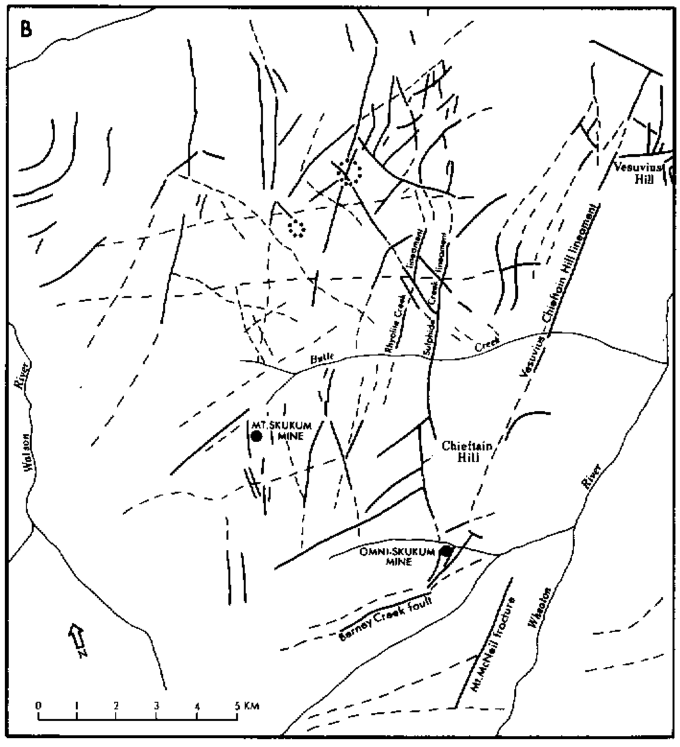


Figure 8. Interpretation of 1:50 000 Landsat TM imagery centered over the Mt. Skukum Volcanic Complex. Solid lines are distinct lineaments, dashed lines are possible lineaments, and dotted circles are anomalous circular features.

because this approach has focused on low-flying aircraft with imaging systems recording several hundred channels of spectral information and is being developed at the expense of what many feel is the most important benefit of the Landsat system--the synoptic view. These efforts have been labeled by Wilson (1986) as, "geodermatology", because it is a two-dimensional approach that takes into account only the surface or "skin" of the earth. The danger of this approach is that the image interpreter becomes singularily interested in determing only the "colour" of a specific spectral response, while taking no interest in understanding the underlying geological environment.

The exploration geologist involved in reconnaissance studies should be interested in images or maps displaying potential fractures and faults, and areas of alteration. No geologist, however, should be gullible enough to think that Landsat imagery can provide specific exploration targets; the intersection of lineaments associated with an area of anomalous spectral responses should not be interpreted as a specific drill site. Sadly enough, some individuals, from university educated geologists to self-taught prospectors, have been led to believe that remote sensing is the panacea they have always desired, that "high-tech" can solve all of their problems. Nothing could be further from the truth.

CONCLUSIONS

Digitally enhanced remote sensing imagery is a valuable tool for exploration geology when interpreted properly and appropriately used. Educated and experienced users of Landsat data realize that the images are invaluable in reconnaissance studies and provide a viable basis for detailed mapping. When interpreted by a geologist knowledgeable about a specific region, the imagery may help in the decision making processes involved in selecting areas for more detailed examination. Combined with the traditional methods of mineral exploration, satellite imagery provides a more cost- effective means for conducting reconnaissance studies.

Specific conclusions and limitations of this study include the following:

1. TM imagery proved useful for mapping at a variety of scales ranging from a regional overview scale (1:1 000 000), for reconnaissance studies (1:250,000), to detailed mapping (1:50,000).

2. The synoptic and multispectral characteristics of Landsat TM imagery were valuable for mapping regional and local structural patterns.

3. The multispectral characteristics of the imagery were useful for detecting areas of strong surface alteration, primarily limonitic and intensely leached areas. This study, however, was not successful in detecting clay minerals associated with hydrothermally altered rocks.

4. The identification and differentiation of lithologic units was not possible because of the presence of lichen on virtually all exposed rock surfaces.

5. The extreme topography of the region and the low sun angle present during image acquisition resulted in dark shadows on northwest slopes that masked ground features.

ACKNOWLEDGEMENTS

This project was supported by the Exploration and Geological Services Division, Department of Indian and Northern Affairs Canada in Whitehorse, Yukon and by a grant from the Boreal Institute of North America at the University of Alberta. Many thanks to S. Morison and G. Abbott for suggesting the study and for their constructive comments. Thanks to Omni Resources Inc. and the Mt. Skukum Gold Mining Corporation for their cooperation and hospitality during field studies. Discussions with A. Doherty, T. Elliot, G. Gossan, L. Dobbins and C. Hart were very helpful. The assistance of J. Hooper in the field investigations was greatly appreciated.

REFERENCES

ABRAMS, M.J., BROWN, D., LEPLEY, L., SADOWSKI, R., 1983. Remote sensing of porphyry copper deposits in southern Arizona; Economic Geology, Vol. 78, p. 591-604.

CAIRNES, D.D., 1912. Wheaton District, Yukon Territory; Geological Survey of Canada, Memoir 31, 153 p.

DRURY, S.A., 1986. Remote sensing of geological structure in temperate agricultural terrains, Geology Magazine, Vol. 123, No. 2, p. 113-121.

DRURY, S.A., 1987. Image interpretation in Geology; Allen and Unwin Ltd., 243 p.

GOETZ, A.F.H., ROCK, B.N., and ROWAN, L.C., 1983. Remote sensing for exploration: an overview; Economic Geology, Vol. 78, p. 573-590.

GOETZ, A.F.N., 1980. Geological remote sensing in the 1980's: in Remote Sensing in Geology (Siegal, B.A., and Gillespie, A.R., editors), John Wiley and Sons, New York, p. 679-685.

HENDERSON, F.B., and ROCK, B.N., 1983. Frontiers for geological remote sensing from space: report of the Fourth Geosat Workshop, Flagstaff, Arizona, June 12-17, 1983.

JENSEN, J.R., 1986. Introductory Digital Image Processing; Prentice Hall, 379 p.

MCDONALD, B.W.R., STEWART, E.B., and GODWIN, C.I., 1986. Exploration geology of the Mt. Skukum epithermal gold deposits, southwestern Yukon; in Yukon Geology, Vol. 1; Exploration and Geological Services Division, Yukon, Indian and Northern Affairs Canada, p. 11-18.

PODWYSOCKI, M.H., SEGAL, D.B., and ABRAMS, J.M., 1983. Use of multispectral scanner images for assessment of hydrothermal alteration in the Marysvale, Utah, mining area; Economic Geology, Vol. 78, p. 675-687.

PRIDE, M.J., 1985. Preliminary geological map of the Mount Skukum Volcanic Complex, 105 D 2, 3, 4, 5; Exploration and Geological Services Division, Yukon, Indian and Northern Affairs Canada, Open File, 1:25 000 scale map.

PRIDE, M.J., 1986. Description of the Mount Skukum Volcanic Complex southern Yukon; in Yukon Geology, Vol. 1; Exploration and Geological Services Division, Yukon, Indian and Northern Affairs Canada, p. 148-160.

ROWAN, L.C., and LATHRAM, E.H., 1980. Mineral exploration; in Remote Sensing in Geology (Siegal, B.S., and Gillispie, A.R., editors), John Wiley and Sons, New York, p. 553-605.

ROWAN, L.C., WETLAUFER, P.H., GOETZ, A.F.H., BILLINGSLEY, F.C., and STEWART, J.H., 1974. Discrimination of rock types and detection of hydrothermally altered areas in south-central Nevada by the use of computer-enhanced ERTS images: U.S. Geological Survey Professional Paper 883, 35 p.

SABINS, F.F., Jr., 1987. Remote Sensing Principles and Techniques, 2nd ed.; Remote Sensing Enterprises, Inc., 449 p.

SCHOWENGERDT, R.A., 1983. Techniques for image processing and classification in remote sensing; Academic Press, Inc., 249 p.

SIBSON, R.H., 1987. Earthquake rupturing as mineralizing agent in hydrothermal systems; Geology, Vol. 15, p. 701-704.

SIEGAL, B.S., and GILLIESPIE, A.R., editors, 1980. Introduction; in Remote Sensing in Geology, John Wiley and Sons, New York, p. 1-2.

SMITH, M.J., 1983. The Skukum Volcanic Complex, 105 D SW: Geology and comparison to the Bennett Lake cauldron complex; in Yukon Exploration and Geology 1982, Exploration and Geological Services Division, Yukon, Indian and Northern Affairs Canada, p. 68-73.

WHEELER, J.O., 1961. Whitehorse map-area, Yukon Territory, 105 D, Geological Survey of Canada, Memoir 312, 156 p.

WILLIAMS, R.S., Jr., et al., 1983. Geological applications; in The Manual of Remote Sensing (Estes, J.E., and Thorley, G.A., editors), American Society of Photography, The Sheridan Press, p. 1667-1951.

WILSON, J.G., 1985. Remote sensing for exploration geology; geodermatology, geomorphology, or both?: Fourth Thematic Conference, "Remote Sensing for Exploration Geology", San Francisco, California, April 1-4, 1985.

WISE, D.U., 1982. Linesmanship and the practice of linear go-art; Bulletin of the Geological Society of America, Vol. 93, p. 886-888.