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THE UNIVERSITY OF ALBERTA

Image Enhancements for Mineral Exploration

by

Peter von Gaza

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF
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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled **Image Enhancements for Mineral Exploration** submitted by Peter von Gaza in partial fulfilment of the requirements for the degree of Master of Science.

J. Ronald Eyton

Supervisor

Arleigh H. Laycock

Date 2/10/89

ABSTRACT

Two papers are presented for the thesis. The first paper is an application of existing techniques and is titled "Enhanced Landsat Thematic Mapper Imagery for Exploration Geology in the Wheaton District, Southern Yukon". The second paper focused on the development of new image processing techniques and is titled "The Perception and Enhancement of Depth in Monoscopic Remotely Sensed Images".

In the first study digitally enhanced Landsat Thematic Mapper (TM) imagery was evaluated as a mapping aid for the exploration geology in the Wheaton District of the southern Yukon. Landsat TM data was digitally processed to enhance lineaments and alteration zones. Geological mapping was conducted at a reconnaissance scale of 1:250,000 for a 45km by 45km area centered on the Wheaton District and at a detailed scale of 1:50,000 for the Mt. Skukum Volcanic Complex. Field investigations showed that the TM imagery was valuable for detecting and mapping small scale geological lineaments and for recognizing limonitic rocks. Detailed field investigations conducted on the Mt. Skukum Volcanic Complex showed that edge enhanced Landsat images were useful for detecting most of the previously mapped faults and fractures and for identifying several dikes. Several unmapped, and potentially significant, lineaments were mapped using the TM imagery. Alteration zones, primarily iron oxide rich rocks, were also mapped successfully.

The second paper introduced new digital image processing techniques for the enhancement of depth perception in visual interpretation. The role of the depth cues in image interpretation was shown to be critical for recognizing lineaments. Three image enhancement techniques were developed. The first technique corrected topographically inverted images by grey scale reversal. This technique is based on the principles involved in the perception of depth from shading. In images where inversion of topography confuses and confounds visual interpretation, simple negatation of the image grey scale was found to be an effective technique for producing images that display proper topographic perspective. A psuedo-stereoscopic enhancement of imagery for displaying changes in grey tones by corresponding changes in brightness *relief* was developed as the second technique. The basis for this technique is the concept that spatial features visible in the digital image topology (a three-dimensional representation of image brightness) provide valuable visual clues that aid in the interpretation of tonal lineaments. A third technique involving cartographic hillshading of the digital image topology was developed as an edge detection technique. Hillshaded image data sets were found to be useful for perceiving subtle details in the geometry of the image topology and proved to be a flexible and dynamic means for conducting lineament analysis.

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Thanks to Dan Hemenway for his seemingly endless patience in assisting me in exorcising the poltergeists that frequently inhabited the computers I worked on. Thanks to all my friends in geography that made my stay memorable and interesting. Finally, a special thanks to Kathy for her patience and support.

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I. GENERAL INTRODUCTION

This thesis is focused on the enhancement of digital Landsat imagery for visual interpretation. The thesis is presented as two papers, with each paper a separate study that is meant to stand alone. Both papers use the same Landsat Thematic Mapper (TM) data and have the same general study area, the Wheaton District in the southern Yukon. The focus of each of the papers, however, is quite different. The first paper is an application of existing techniques and is titled "Enhanced Landsat Thematic Mapper Imagery for Exploration Geology in the Wheaton District, Southern Yukon". The second paper is about the development of new techniques and is titled "The Perception and Enhancement of Depth in Monoscopic Remotely Sensed Images".

The first paper describes a study undertaken for the Department of Indian and Northern Development (DIAND), Whitehorse, Yukon. I was approached by a DIAND geologist in the summer of 1986, while working as a field assistant on a DIAND supported study in the St. Elias Mountains, concerning a study in the Yukon that would demonstrate both the usefulness and limitations of remote sensing for mineral exploration. At the time of this meeting no studies on remote sensing for mineral exploration in the Yukon had been published. More importantly, it was felt that misconceptions concerning the role of remote sensing in mineral exploration needed to be addressed. The overall objective of the study was to demonstrate some of the most commonly used image processing techniques for mineral exploration and to evaluate their application at specific study sites in the Yukon. Two study sites were chosen; The Wheaton District and The Klondike District. These two areas were selected because of their contrasting physiography and geology. The month of May was spent in developing image products for both areas and then field studies were conducted during June, July, and part of August. Of the two areas investigated, the Wheaton District study is included in this thesis and is also currently being published in *Yukon Geology*. The Klondike

District study, as approached in the summer of 1986, was less successful and has evolved into another study that is presently being conducted in cooperation with Jim Mortensen of the Geological Survey of Canada.

The second paper was developed as an outgrowth of the first paper and from an interest in computer-assisted cartography. In the first study, interpretation of imagery by myself and others made it clear that individual analyses of the same imagery were quite often significantly different. These observations lead to a review of the basic literature on the perception of depth in imagery, especially how topography is perceived by the human visual system. This literature on "scene understanding" resulted in a search for certain cartographic techniques that could be used to consistently extract image information. The basic idea was to utilize cartographic methods for producing map images that would convey the desired spatial information. This study then became a blend of computer-assisted cartography and remote sensing.

II. ENHANCED LANDSAT THEMATIC MAPPER IMAGERY FOR MINERAL EXPLORATION IN THE WHEATON DISTRICT, SOUTHERN YUKON

Landsat Thematic Mapper (TM) imagery was evaluated as an aid for mineral exploration in the Wheaton District of the southern Yukon during the field season of 1987. This paper is a brief description of some commonly used digital image enhancement techniques, followed by a discussion of the application of these techniques to the geology of the Wheaton 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 spatial 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 used in combination with all other available exploration methods is an 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 considered quite 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). Geologists for some time have realized that 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 spatial distribution of potential 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 ability to view extensive areas using Landsat imagery has provided the geologist with a valuable tool for mapping potential fracture and fault patterns, especially in areas where very little is known about the geological environment.

The multispectral characteristics of the Landsat sensing systems have provided geologists with a means for detecting and mapping altered rocks (primarily limonitic rocks), and with the addition of the TM sensor system in 1982 to the Landsat platform, the potential for detecting hydrothermally altered rocks (Henderson and Rock, 1983) has improved considerably. The inclusion of TM band 7 centered at 2.2 μm 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 often associated with ore deposits, indicates likely areas for field exploration.

Data

The digital image data set 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 85km by 85km, 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. II-1) lies mostly within the Wheaton District, on the eastern edge of the Coast Mountains, just north of the British Columbia boundary. The district is approximately 50km south-southwest of Whitehorse. While the general study area covers a 45km by 45km square, the primary focus of this paper will centre on a 15km by 15km 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 1km 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 extend up hillsides to an elevation of 1300 metres. Willows are abundant along flood plains, while dwarf birch are plentiful in the higher valleys. Upland plateaus, generally occurring at elevations above the tree line, are characterized by alpine vegetation, including ericaceous shrubs and prostrate willows, and a ground cover of mosses and lichen.

A description of the basic geology is confined to the Mt. Skukum Volcanic Complex as it is the focus of the study. The Skukum Volcanic Complex, the northern-most

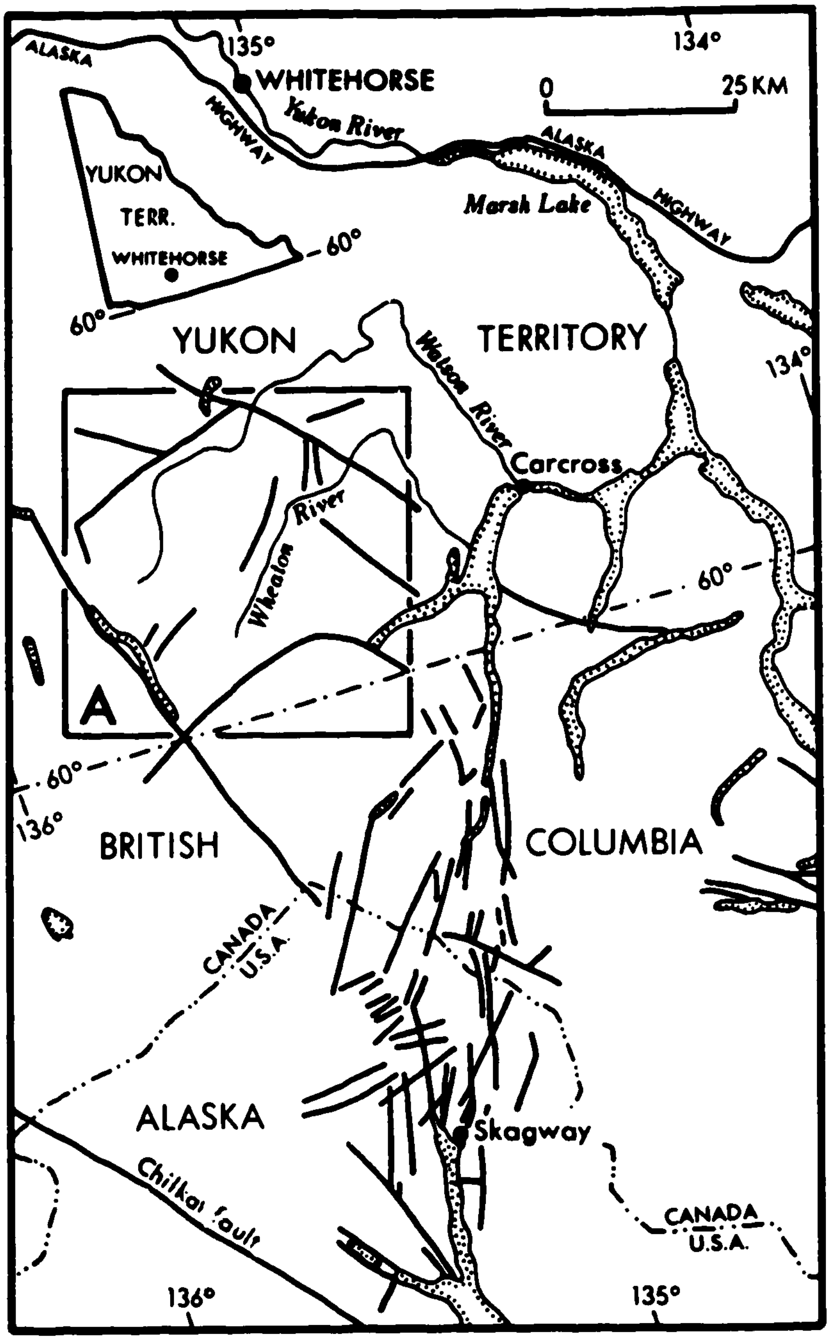


Figure II-1. Regional lineament map interpreted from a 1:1,000,000 TM Landsat scene and showing the location of the general study area (box A).

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 of the Ruby Range Batholith 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 in the area, focused primarily on locating epithermal gold deposits. The Mt. Skukum deposit is hosted 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 studying ore 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 association (Elliot, 1988, pers. comm.). The Skukum Volcanic Complex may be analogous to the 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 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. 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 35mm Dunn Camera or an 8x10 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 of particular importance 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 transforming 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 or retaining topographic expression. (Crippen et al., 1988). 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. II-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 45km by 45km 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 (Fig. II-2), and a spatially filtered band 5 black and white image (Fig. II-3), 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. II-3 represent limonitic rocks. Areas characterized by intensely leached rocks had strong spectral responses in all bands, and were easily recognized on the imagery as the brightest reflectors. Field inspections revealed that these leached areas are sometimes characterized by hydrothermal alterations. Alterations in the Mt. Skukum

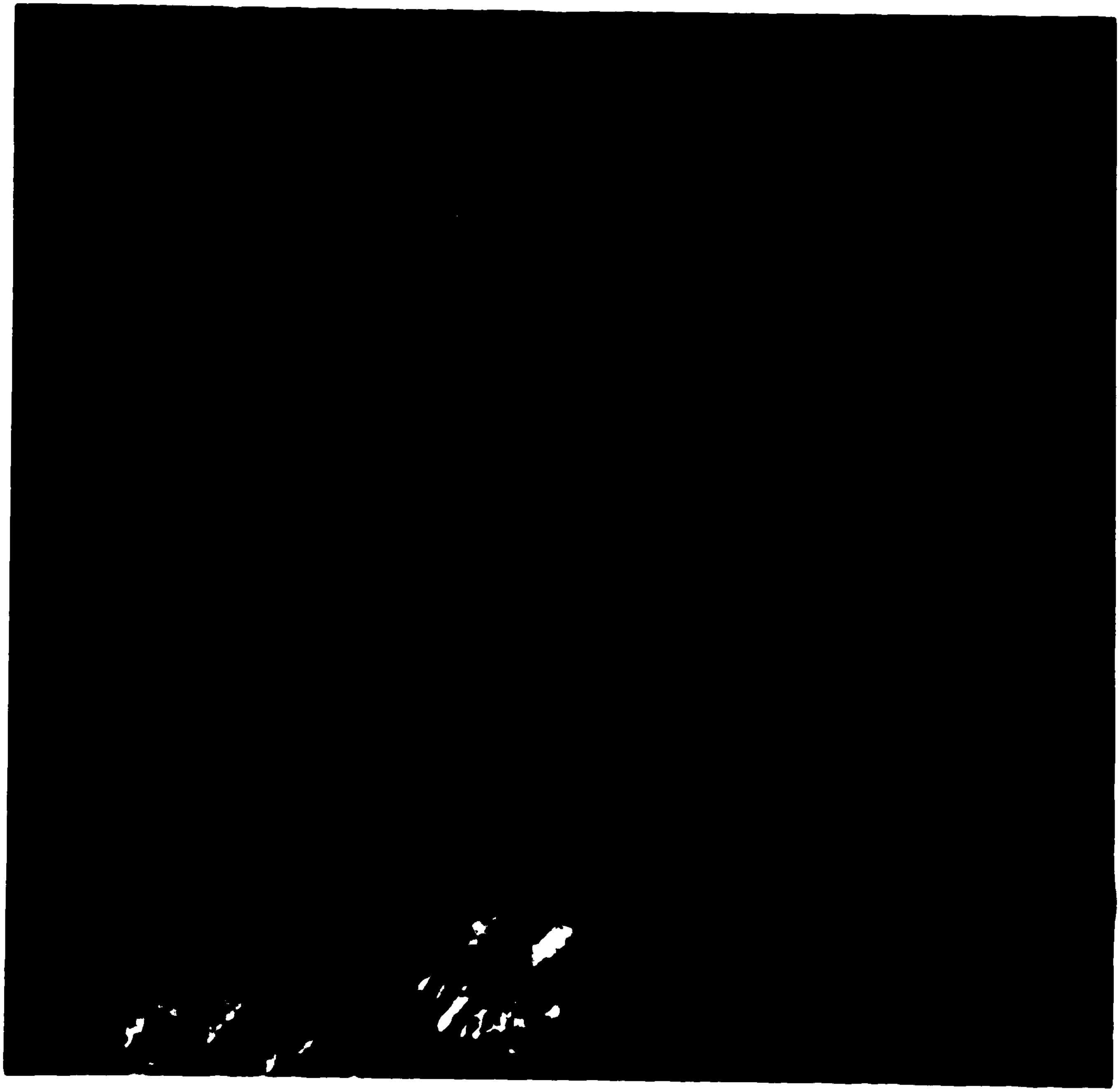


Figure II-2. False colour composite (1:250,000) of the general study area. TM bands 5,4,and 3 are assigned red, green, and blue respectively. The image was acquired September 6, 1986 (path 59, row 18).

Figure II-3. Edge enhanced Landsat TM band 5 image (1:250,000) of the general study area.

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. II-4) represents a conservative interpretation of the regional lineament pattern. Major lineaments were easily seen in Fig. II-2 and Fig. II-3. The northwest trending fault mapped by Cairnes (1912), along the north side of the Watson River, exhibited a strong topographic expression. A series of 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 1-4km wide, 35km long zone of semi-brittle to ductile deformation 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 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 15km by 15km 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. II-5), spatial filtering, normal and IR false colour compositing, band ratioing, and principal components analysis.

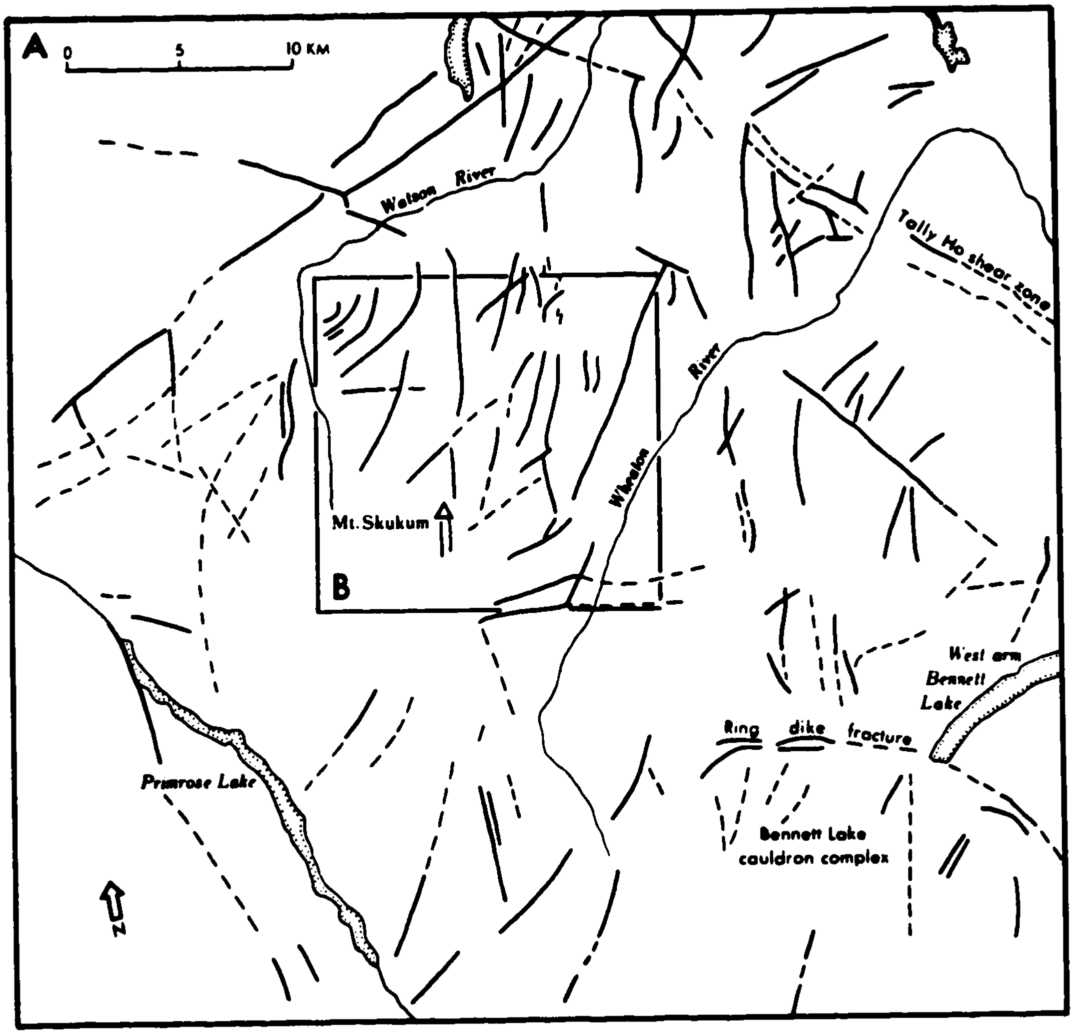


Figure II-4. Interpretation of lineaments on 1:250,000 TM imagery centered over the general study area and showing the Mt. Skukum study area (box B) in Fig. II-8. Solid lines are distinct lineaments and dashed lines are possible lineaments.

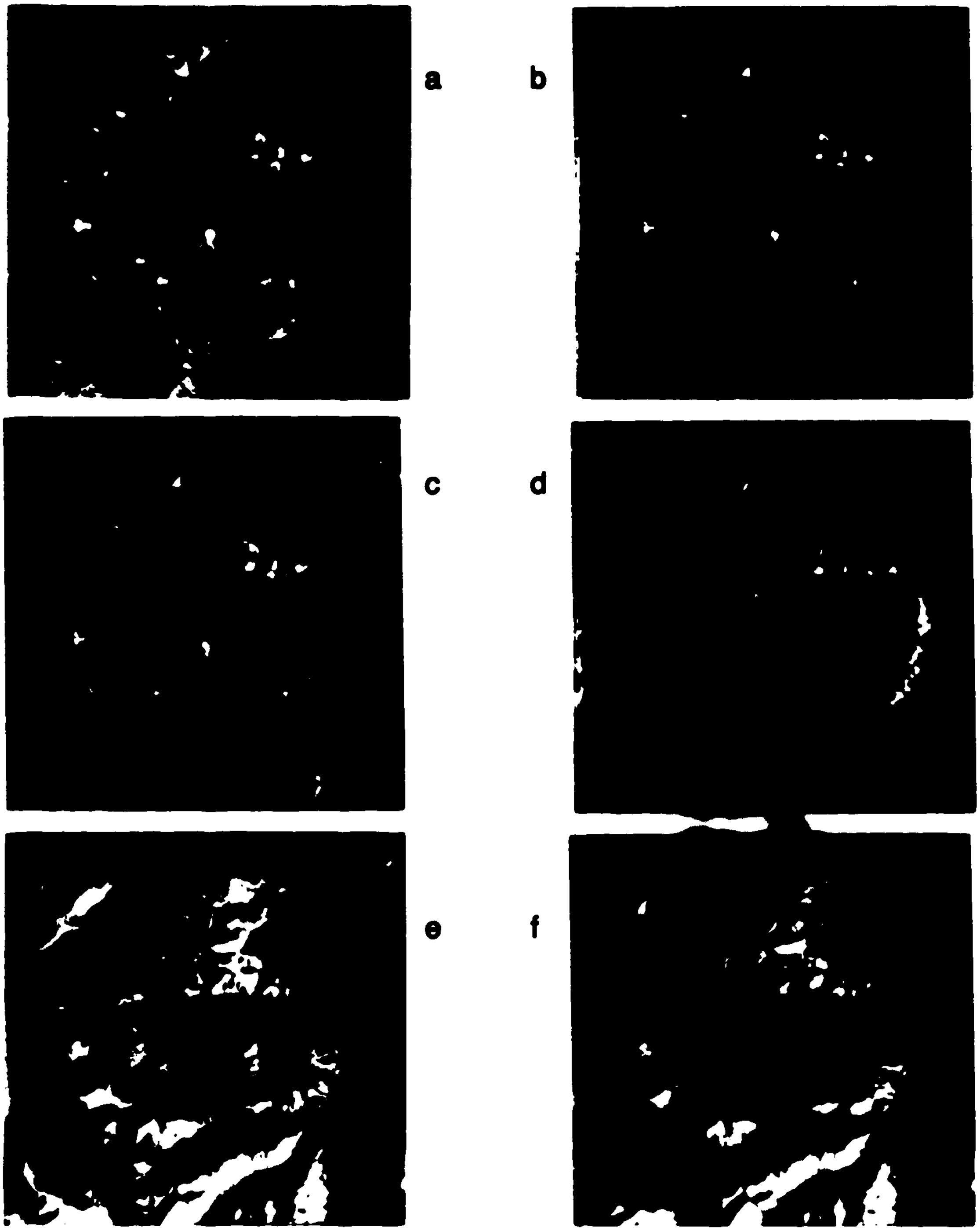


Figure II-5. Contrast stretched images of Landsat TM bands. (a) TM1: reflected blue-green light, .45 - .52µm, (b) TM2: reflected green light, .52 - .60µm, (c) TM3: reflected red light, .63 - .69µm, (d) TM4: reflected infrared radiation, .76 - .90µm, (e) TM5: reflected infrared radiation, 1.55 - 1.75µm, (f) TM7: reflected infrared radiation, 2.08 - 2.35µm.

Alterations

A series of ratio and 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. II-6) 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 rocks that exhibit a red colouration. The 3/1 ratio image removed the confusion that existed in the band 3 image between altered areas and snow (compare Fig. II-5c and Fig. II-6). 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 within areas dominated by limonitic rocks were used as training samples; the intensely altered areas of Sulphide and Rhyolite Creeks were chosen as the specific test sites. Most of the clay alterations were associated with highly leached areas which had very strong spectral responses on 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 bedrocks 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 non-arid, 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. PC images 1,3, and 4 were used to create a color composite. These three components were chosen to construct the composite because

Figure II-6. Density sliced band ratio (3/1) image of the Mt. Skukum Volcanic Complex. Altered rocks, primarily limonite, have been coloured from red (highly altered) to yellow (moderately altered).

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 (not shown) 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 in colour, 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; there was a greater chance of potentially missing an altered area because these areas did not stand out in contrast to the rest of the image.

Lineaments

The identification of local lineaments was accomplished by examining a spatially filtered band 5 image (Fig. II-7) and the false colour composite. Lineaments mapped from both images (Fig. II-8) were compared to existing geological maps (1:25,000) compiled by Smith-Pride (1985) and checked in the field. Analysis of lineaments 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 lineaments 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 of these lineaments were adjacent to

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

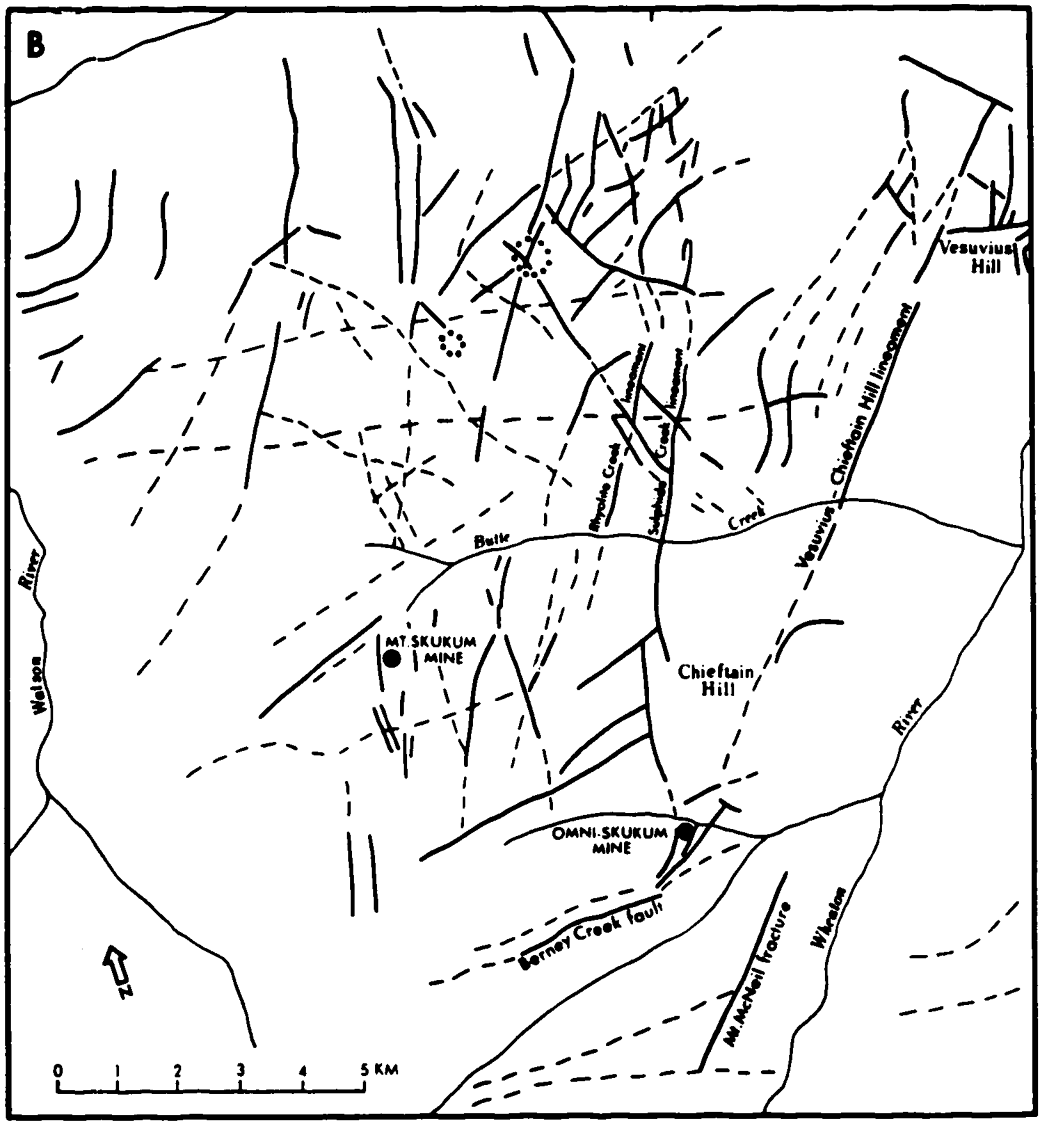


Figure II-8. Interpretation of 1:50,000 Landsat TM imagery centered over the Mt. Skukum Volcanic Complex. Solid lines are distinct lineaments, dashed lines are possible lineaments, and dotted circles are anomalous circular features.

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 author 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 15km in length; these were given the preliminary names of the Vesuvius-Chieftian Hill, the Sulphide Creek and the Rhyolite Creek Lineaments.

The Vesuvius-Chieftian Hill Lineament extends from north of Mt. Vesuvius, across Summit Creek, across Chieftian 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 Chieftian Hill before becoming part of Sulfide Creek; to the north, the same lineament becomes an inconspicuous 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 Sulfide 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 aeri surveys conducted for the Mt. Skukum Gold Mining Corporation over these li[illegible] 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.

Misconceptions of Remote Sensing

The experience of the author 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 using 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 of 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 unrealistic 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 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 determining 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 <u>should be</u> 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.

REFERENCES

Abrams, M. J., Brown, D., Lepley, L., Sadowski, R., 1983. Remote sensing for 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, 153p.

Crippen, R.E., Blom, R.G., and Heyada, J.R., 1988. Directed band ratioing for the retention of perceptually-independent topographic expression in chromaticity-enhanced imagery; International Journal of Remote Sensing, vol. 9, no. 4, p. 749-765.

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., 243p.

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 1980s: in Remote Sensing in Geology (Siegal, B.S., 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, 379p.

McDonald, B.W.R., Stewart, E.B., and Godwin, C.I., 1986. Exploration geology of the Mt. Skukum epithermal gold deposit, 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, 105D-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 Gillespie, 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, 35p.

Sabins, F.F., Jr., 1987. Remote Sensing Principles and Techniques, 2nd ed.; W.H. Freeman and Company, 449p.

Schowengerdt, R.A., 1983. Techniques for Image Processing and Classification in Remote Sensing; Academic Press, Inc., 249p.

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, 105D, Geological Survey of Canada, Memoir 312, 156p.

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 Photogrametry, The Sheridan Press. p. 1667-1951.

Wilson, J.G., 1985. Remote sensing for exploration geology: geodermatology, geomorphology, or both? in Proceedings of the International Symposium on Remote Sensing of Environment fourth Thematic Conference, Remote Sensing for Exploration Geology (Ann Arbor: ERIM), p. 195-203.

Wise, D.U., 1982. Linesmanship and the practice of linear geo-art; Bulletin of the Geological Society of America, vol. 93, p. 886-888.

III. THE PERCEPTION AND ENHANCEMENT OF DEPTH IN MONOSCOPIC REMOTELY SENSED IMAGES

INTRODUCTION

This paper is focused on understanding and improving the ability of the human visual system for perceiving form in monoscopic remotely sensed images, particularly for geological lineament analysis. The role of visual depth cues, especially shading information, for the perception of depth in visual interpretation is reviewed, and image processing techniques for enhancing depth cues as an aid for lineament analysis are presented. This paper is best understood when applied to digital image data sets that have strong topographic expression.

The ability of the human visual system for perceiving depth is essential in the visual interpretation of remote sensed images. The perception of depth is particularly important for the photogeological interpretation of images because geologically significant materi and structures are identified primarily by their surface expression of geomorphological properties. Visual depth clues provided by the expression of topography in monoscopic images provide the primary means for extrapolating lithologic and structural information. In traditional photogeology, it is recognized that although the colour (spectral signature) and patterns of colours of surface materials may be valuable for geological investigation, they are of secondary importance compared to the value of the expression of topography within the imagery (Wilson, 1985; Tator et al.,1960; and Lueder, 1959). In monoscopic image interpretation the shadows cast by landforms, and the differences in illumination of a landform, provide the primary visual clues for extrapolating shape, form, and pattern. The recovery of depth information, and therefore topographic expression, generally results from the global assimilation of light and shade patterns from an entire image. Alternatively, stereoscopic viewing of imagery provides a means for actual three-dimensional viewing, creating a mechanism in which landform differences relating to structure and lithology may be visually identified by actual *relief* displacement.

Having established that the expression of topography is valuable in photogeological interpretation, it is important to understand how topography is expressed in the digital data. The visual inspection of an image by a trained interpreter will reveal both ground illumination and ground reflection information, but inspection of a single pixel will reveal no such division of image information. A single pixel represents the integration of both surface reflectance and topographic information. The brightness of a pixel is a function of the surface geometry and the reflectance properties of the surface material. In terrains of variable relief, topography may play an important role in determining scene radiance. In monoscopic images topography is perceived because the human visual system is normally able to isolate illumination information from surface reflectance information, even though the two types of information are integrated as one indistinguishable measure in individual pixels (see Crippen et al., 1988 for a complete discussion on the expression of topography in digital imagery).

In this paper the principles relating to the perception of depth of topography are applied to the psuedo-topography describe by the topology of a digital image data set. Fig. III-1 is a perspective plot of the digital record of reflected radiation, and represents a three-dimensional spatial distribution of image data. The spatial distribution of image information, in a three-dimensional sense, will be refered to as "digital image topology". The perspective plot of the digital image topology shows a psuedo-surface in which topographic and ground reflectance information are no longer separable. Differences in recorded radiation intensities are seen as differences in *relief*, while distinct spatial features in the perspective plot are seen as psuedo-landform features (valleys, ridges, scarps, etc.). Inspection of the digital data in image form (Fig. III-2) shows that distinct tonal differences and boundaries, particularly lineaments created by the differential illumination of the topography, are detectable as sudden breaks in slope in the

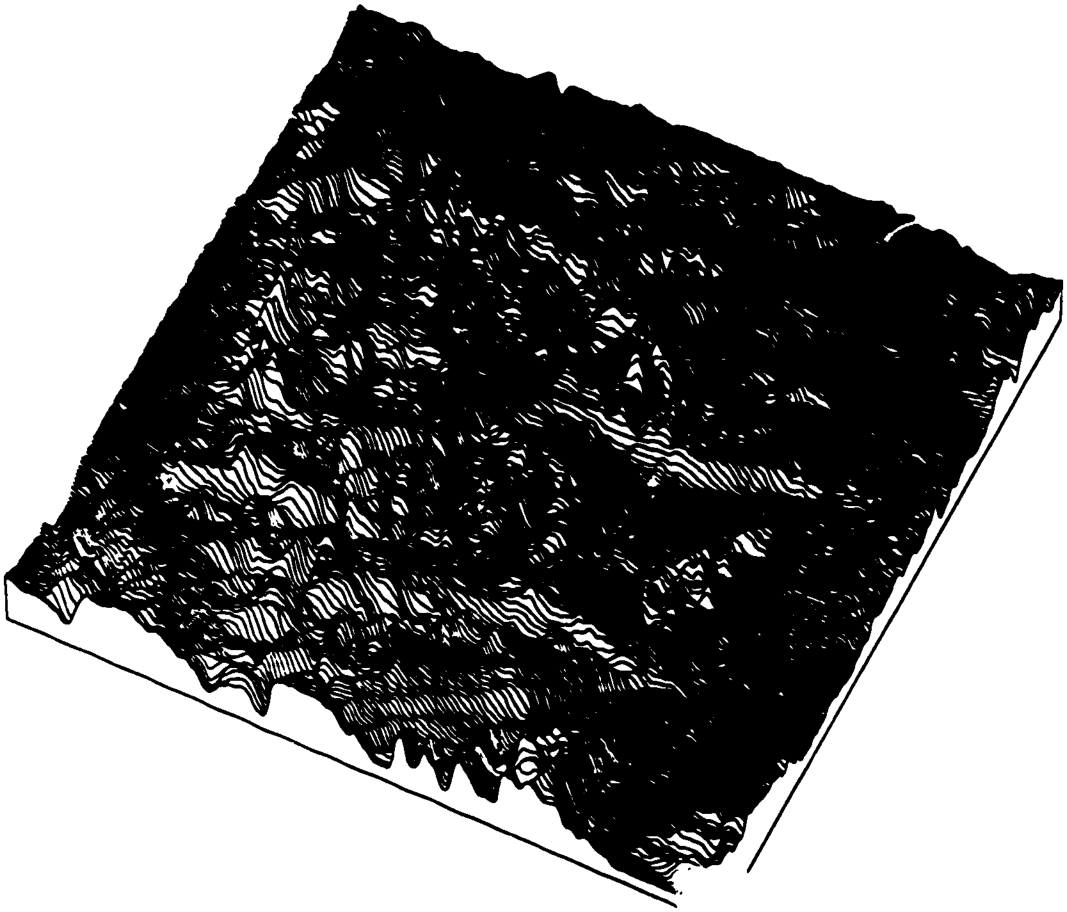


Figure III-1. Perspective plot of TM band 5. The data set has been smoothed using a 3x3 low-pass filter. The viewing perspective is from the SE (azimuth=154°) at an observer altitude of 50°.

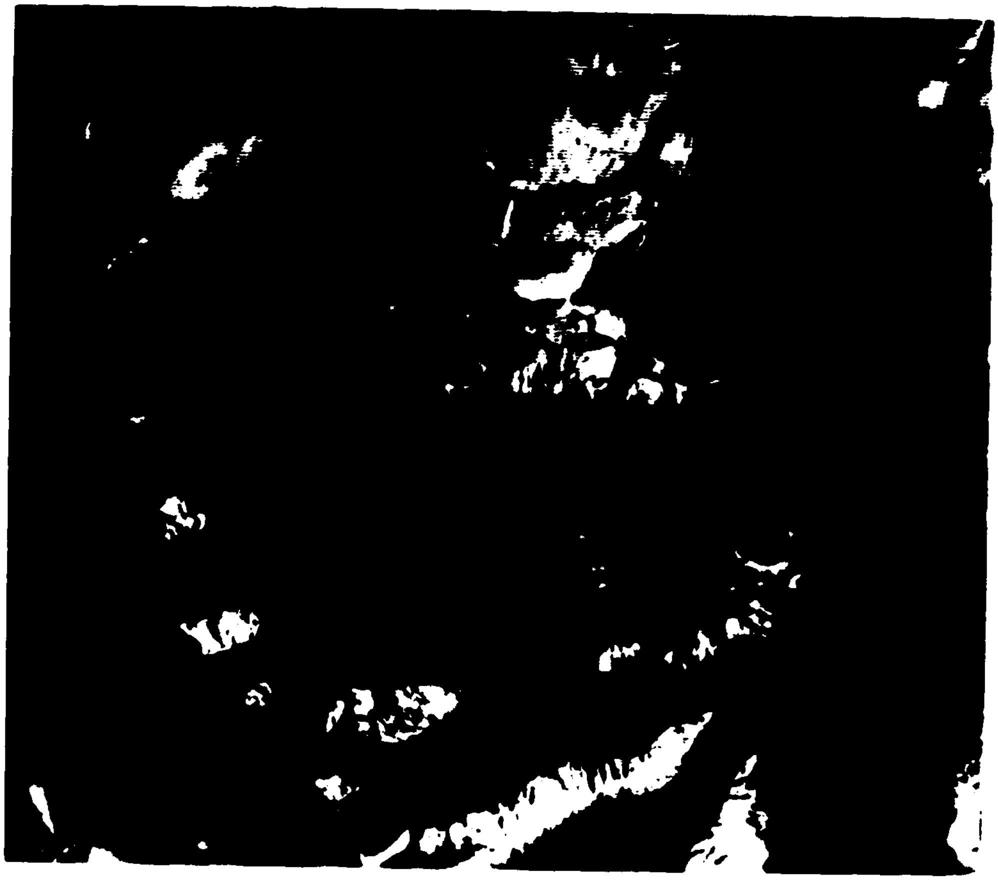


Figure III-2. Landsat TM band 5 image of the Mt. Skukum area, Wheaton District, southern Yukon. Image has been linear contrast stretched with saturation.

perspective plot of the digital image topology.

The general objective of this paper is to discuss the depth cues used by the human visual system in perceiving depth in monoscopic images, and to discuss image processing techniques that can be used for enhancing spatial features in the digital image topology as an aid for photogeological interpretation, particularly for lineament analysis. The paper is presented in three major sections. The first section is a discussion of the perception of depth in remotely sensed images, focusing on why topographic expression sometimes appears inverted. A simple computational method is also presented for correcting inverted digital images. The second section is a discussion of the stereoptic capabilities of the human visual system and how the inherent digital image topology of an image can be used for producing stereo models in which changes in radiation intensity are perceived by changes in *relief* of the brightness psuedo-topography, as well as by changes in grey tones. The last section is a presentation of a directional filtering technique in which the digital image topology is treated as a psuedo-topography and is illuminated using a Lambertian light model to enhance lineament expression for visual detection.

Data and Study Site

The data set used in this study was a 225 km^2 subset of a Landsat Thematic Mapper (TM) digital imagery centred over the Mt. Skukum Volcanic Complex in the Wheaton District of the south-west Yukon. The topography of the complex is rugged and has been highly modified by pleistocene glaciation. Valleys have high relief (700-1000m) and deeply dissect the entire the entire complex. The terrain varies from broad upland plateaus to steep serrated ridges. Cirques are very common in the area. Geologically, the complex is a series of Paleocene-Eocene volcanic rocks that have been deposited unconformably on Cretaceous granitic rocks and older metasedimentary rocks. The complex is highly fractured, is intruded locally by felsic stocks and dikes, and is fault bounded. This area is currently a "hotbed" of exploration activity centred on locating epithermal and mesothermal gold deposits.

IMAGE INVERSION

The Perception of Depth from Shading

When viewing a monoscopic image the human visual system is able to recover the three-dimensional shape (form) of objects by using perceived variations in image intensity (Ramanchandran, 1988; Woodham, 1984; Todd and Migolla, 1983; Yonas, et al., 1979; and Arnheim, 1974). This process is also refered to as the perception of depth from shading. Horn (1982) defines shading as "the dependence of apparent brightness of a surface element on its orientation with respect to the light source(s) and viewer". *Chiascuro*, first described by Leonardo da Vinci over 500 years ago, is an early example of a technique used in painting for imparting three-dimensional shape by the use of light and shade (MacCurdy, 1938). Cartographers have also used techniques of shading on topographic maps to make the perception of topograpic form more apparent (Robinson, et. al.,1978).

The perception of topography, in remotely sensed images (recording reflected electromagnetic radiation), is an unconscious response of the human visual system to the global pattern of light and shade in the scene (more commonly refered to as shading information). The shading in an image is a result of differences in illumination due to topography and to the presence of shadows. The degree to which topography is expressed in an image is strongly related to the orientation of the sun during image acquisition. An image acquired with a relatively low solar elevation will impart a greater sense of depth than an image acquired with a high solar angle; the contrast of light and shade will be more pronounced in the former, while the perception of depth in the latter will be more ambiguous because of the absence of distinct shading depth clues. Ramanchandran (1988) describes two basic *rules* that seem to govern the perception of depth from shading in monoscopic images in the human visual experience: 1. only one light source illuminates an image and this source is above the horizon and to the north, and 2. that the impression of depth is the result of the unconscious assimilation of global information involving most of the image.

Although the human mind is able to sort out the complex pattern of light and shade in a monoscopic image in order to recover an impression of depth, the proper orientation of the topography is not always instinctively recognized. Ramanchandran (1988) states that the viewers objective knowledge of up and down does not influence the visual system's depiction of perspective, but rather perspective is determined by the orientation of light and shade patterns on the retina. This is analogous to the fact that the form of many landforms cannot be determined from a standard topographic map without interpretation of drainage patterns or knowledge of contour values; with the addition of simulated shadows from a sun in the north, the form of the topography becomes readily apparent. This last example illustrates a well known fact that in the recovery of an impression of depth in monoscopic images that the direction of illumination is crucial and controls whether a form will appear convex or concave. For reasons that are not well understood, the human visual system assumes that there is only one light source and that the illumination is from above the horizon and generally from the north. An often used example demonstrating the effect of varying illumination direction is the perception, in a monoscopic image, of a simple form such as a sphere. When illuminated from the north the sphere appears in positive relief (correct perspective), but when illuminated from the south the sphere appears as a depression (inverted perspective). When the sphere is illuminated at directions approximately 90 degrees from north, the ability to perceive the proper form becomes more difficult and ambiguous because the brain shifts back and forth between concave and convex perspectives. This again relates to the direction of illumination that is expected. In the case the of the sphere the correct perspective can be achieved by simply rotating the image to move the illumination source to the north. However, when more complex, non-uniform shapes are illuminated, the rotating of the image to correct relief perspective may result in unfamiliar image patterns that confuse and confound visual interpretation.

Landsat Image Inversion

The principles governing the perceived positive or negative relief of simple shapes in monoscopic images can also be applied to the perception of much more complex shapes. The TM band 5 image shown in Fig. III-2 was acquired with a south-east direction of illumination (solar azimuth of 153 degrees) and a solar elevation of 34 degrees. The image area is characterized by rugged topography and a 1000 metres of relief, producing pronounced differences in illumination. Shadows cast on northwest slopes are extensive and dark because of the low solar angle and the image displays a strong contrast between highly illuminated and shaded areas and imparts a strong impression of depth. The direction of illumination is from the south-east and the image topography appears inverted to almost all viewers. For example, Butte Creek, within a major valley oriented east-west through the middle of the image, is perceived as the crest of a ridge. This inversion of the topography results because the human visual system is assuming a solar azimuth from the north. The south-east orientation of the sun results in the north side of the creek being highly illuminated and the south side being deeply shaded. The mind responds to this light and shade pattern by creating a ridge instead of a valley, which for a northern illumination direction would be correct. Rotating Fig. III-2 by 180 degrees, in most instances, results in a properly perceived topography because the direction of illumination in the image is now from the north-west. Fig. III-3 shows the effect and resulting confusion from successively rotating a subset of Fig. III-2 90 degree increments.

Most individuals shown the image displayed in Fig. III-2 almost always saw the topography inverted, and by rotating the imagery 180 degrees saw the topography in its

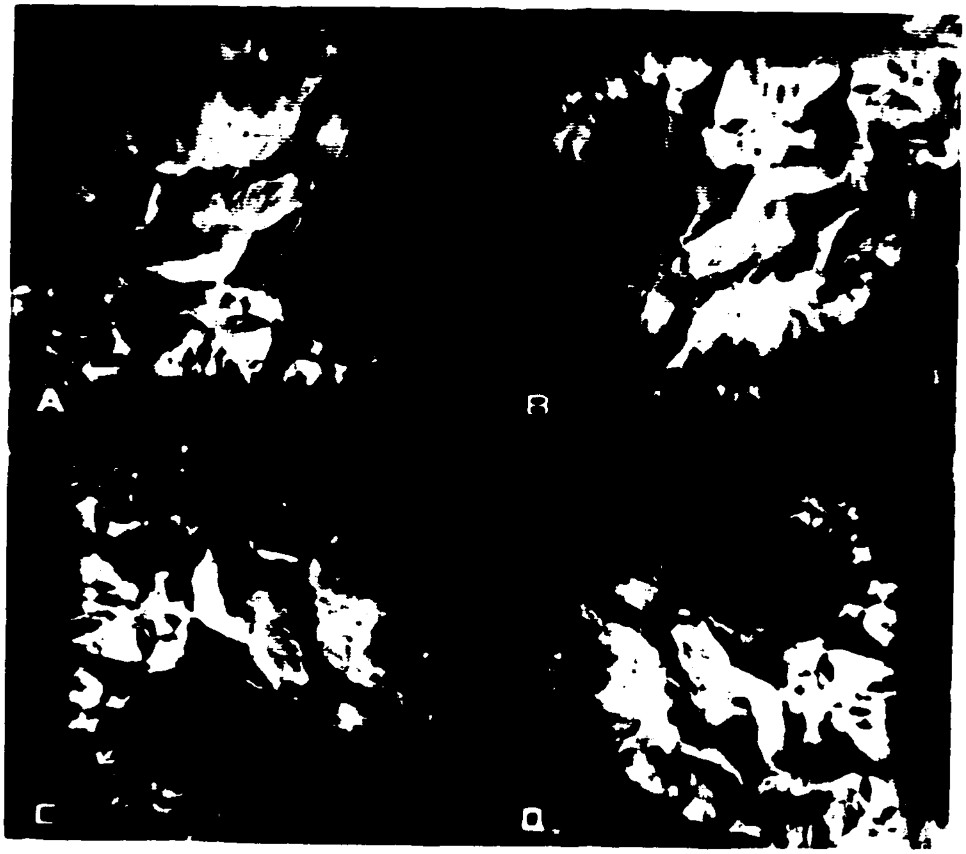


Figure III-3. Rotated subset of Fig. III-2 showing the effect of the direction of illumination on the perception of topography. (a) southeast illumination, (b) northwest illumination, (c) southwest illumination, (d) northeast illumination. Perception of topographic form in this image varies considerably among viewers.

proper perspective. Invariably these individuals had little or no experience in interpreting satellite images. For example, a group of geologists familiar with the area used for this study, but also with no prior experience of interpreting satellite images, also perceived the topography as inverted. The inversion of the topography made identification of topographically expressed structural features contained in the images more difficult. Most geologists found the images confusing because of their objective knowledge of the topography. Rotating an image 180 degrees to obtain a northern illumination and thus the proper topographic perspective, resulted in an even more confusing image to those familiar with the area. After prolonged viewing of the images or repeated viewing of the images at later dates, many viewers found that they saw the proper topographic perspective at any image orientation. This accomodation effect was most pronounced in viewers with photo-interpretation backgrounds.

General observations from this paper indicate that the perception of the orientation of topography, in complex images, irrespective of the angle of illumination, seems to be strongly influenced by the viewers experience in interpreting remotely sensed images and their familiarity with a given image. Some individuals with strong backgrounds in the interpretation of aerial photographs saw the topography correctly oriented in virtually any illumination direction. This ability to see the proper topography regardless of the illumination is thought to be associated with the interpreters ability to mentally shift from an intuitive, global mode of perception, to an analytic mode of thinking where objective knowledge of local image featured can override the direction of illumination *rule*. The objective identification of geomorphologically expressed features such as rivers, broad valleys, drainage patterns, etc. seems to provide the necessary clues for recovering proper topographic perspective. The apparent ability of the mind to override the illumination *rule* was also noted by Ramachandran (1988). These ideas are similar to the cognitive-shift model for the teaching of drawing developed by Edwards (1979).

Excluding the right and left portions of Fig. III-2, which correspond to wide valley bottoms and are easily interpreted as lowland areas, the determination of actual form becomes more difficult as there are no obvious landform features or patterns to provide adequate cues to the proper perspective. In images where there are no distinct landforms, it is suspected that the brain relies entirely on depth cues provided by illumination.

Digital Correction of Topograpically Inverted Image

A simple but effective method is presented for correcting images in which topography is perceived as inverted because of southeast illumination present during image acquisition (characteristic of Landsat imagery for most of North America). In this method the direction of illumination is artificially moved to the northwest to meet expectations of the human visual system. This is accomplished by simply inverting the grey scale of the image. An inversion is obtained by subtracting a digital number (DN) from 255 for every pixel in the raw data set, which then becomes the transformed pixel value. Fig. III-4 is a digitally inverted image resulting in a properly oriented topography. A comparison of Fig. III-4 with Fig. III-2 shows that the correct topography is more easily perceived in the digitally inverted image than in the original image. The obvious disadvantage to this technique is that brightness values are *negative* brightness values. This inversion of grey tones may cause difficulties in objectively relating grey tones to surface materials. The digital inversion of very dark objects, such as shadows, may result in areas of extreme brightness that are saturated and tend to visually wash out adjacent areas. The problem of saturation is most evident in the reflected infrared bands for features such as clear lakes that absorb almost all incident energy, and shadows that represent areas that receive little or no incident energy. By desaturating the extreme DN values of inverted images a more visually pleasing and

Figure III-4. Correction of topographically inverted band 5 data. The original image grey scale has been reversed, resulting in the inversion of the shading pattern of the image; the illumination source has been artificially moved from the southeast to the northwest. Comparison with Fig. III-2 indicates that proper topographic expression is perceived more easily in this image.

interpretable image is produced.

A false colour composite with perceived inverted topography is corrected by inverting each individual band before compositing. Bands 5,4, and 3 were used to produce the false colour images shown in Figures III-5 and III-6. Fig. III-5 is the original composite, and displays an inverted topography; Fig. III-6 is the corrected composite and displays a proper topographic perspective. Comparison of the two images shows that the corrected composite is displayed in complementary colours compared to the original composite. For example, if a particular pixel is displayed as red on a video screen (red gun full intensity, green and blue guns off), in the inverted image that pixel will appear as cyan (red gun off, green and blue guns full intensity). In false colour images the colours of surface materials do not correspond to the normal visual experience, therefore the inversion of the colour scheme is not detrimental to the interpretation of the image. The ability to differentiate between materials has not been reduced; only the colours have been changed.

An alternative approach for correcting inverted topography in colour composites is accomplished using an Intensity-Hue-Saturation transform (see Gillispie, et. al., 1986 for a discussion of this procedure). The intensity component, which contains most of the topographic expression of the data (and albedo information), is inverted. Hue and saturation, which describe chromaticity and are used to differentiate between surface materials, are not modified. The inverted intensity component and the hue and saturation components are then transformed back into red, green, and blue colour space. The resulting image will have a proper topographic perspective, while retaining the basic colour scheme of the uncorrected composite, although the intensity expression of the colours will be different.

Figure III-5. False colour composite with bands 5,4, and 3 coloured red, green, and blue respectively. Intensity variations (shading pattern) in the composite result in the perception of an inverted topography for most viewers.

Figure III-6. Correction of inverted topography in a false colour composite (Fig. III-5). Inverting the grey scale of each image results in a composite that displays the complementary colours of the original (Fig. III-5).

PSUEDO-STEREOSCOPIC ENHANCEMENT

Stereoptic Vision

The actual perception of depth in the human visual experience is largely due to the stereoptic capabilities of the eye-brain system. The human visual experience of depth is binocular and based on the fact that each eye sees the same scene from a slightly different perspective. This results in a relative change of position of an object in the retinal image of one eye relative to the other. This relative difference is termed parallax and is the basis for all stereoscopic vision, or stereopsis. Each eye in effect is recording a slightly different monoscopic image of varying light and colour, which are then mentally fused to produce a three-dimensional model, or stereo model.

The perception of depth by stereoptic vision is much more real than the impression of depth from a monoscopic image In a single image the perception of depth is recovered by shading information, and although quite useful, the effect is only an impression. On the other hand, a stereo model of an image displays form in an actual three-dimensional measurable model.

Stereoscopic viewing of satellite images is possible when the base-height ratio of overlapping image pairs is large enough to produce detectable vertical exaggeration (Sabins, 1987). Landsat images, both Multispectral scanner system (MSS) and TM, are used to produce stereo models where there is sufficient overlap between adjacent orbit paths. The base-height ratios, however, are generally not great enough to produce a strong sense of surface topography, and at higher latitudes where flight paths converge, the base-height ratio is insignificant. The launch of the SPOT satellite has greatly improved the ability to acquire pairs of images that have relatively large base-height ratios. The SPOT satellite is better suited for acquiring stereo pairs of images because the imaging system is capable of off-nadir viewing through a range of 27 degrees from vertical. This provides a means for repeated viewings of the same scene from different orbital positions.

Another method used for viewing Landsat images stereoscopically has been accomplished by inducing synthetic stereo into a single image (Batson et al., 1976). This method induces parallax relative to the elevation value of a corresponding registered data set. The amount of parallax, induced, is operator defined. The parallax induced image is refered to as a stereoscopic mate of the original. Stereo models produced using this method impart an artificial topography that may be valuable for interpreting three-dimensional structural features not apparent in the original. The introduction of synthetic parallax into an image is limited by such factors as the generation of accurate digital elevation models (DEMs) and the fact that registration of image data and DEM data is costly and laborious.

A Psuedo-Stereoscopic Enhancement Technique

A technique is presented for the enhancement of tonal differences by exploiting the inherent digital image topology of the image data and is termed the psuedo-stereoscopic enhancement technique. The basis for the technique is the introduction of parallax into an image by shifting each pixel in the column direction as a function of the pixel brightness. This procedure shifts one row of the image at a time and can be used to produce a right or left stereomate from the original image. A more detailed description of the parallax induction methodology and the computer code can be found in Eyton (1984). The objective in the application of this technique is to produce a three-dimensional image in which changes in grey tones are also expressed by changes in image *relief*, thereby adding another depth cue that can be used by the visual system in interpreting spatial information.

The introduction of parallax into an image data set by the relative shifting of individual pixels may result in computational problems. The data set used for this study displays both dense shadows and strong highlights creating areas of high contrast. These factors result in an digital image topology characterized by well developed *relief* which is manifested as sudden changes in slope (Fig. III-1). Areas of very high image contrast, expressed as cliffs in the digital image topology, may result in pixels of large brightness values being shifted past adjacent pixels of small brightness values. This can cause serious computational problems; the limitations of the program in handling the extreme contrast found in image data can be overcome by utilizing a 3x3 low-pass smoothing filter. Smoothing the data, however, results in a loss of high-frequency spatial information that is valuable for the detection of subtle edges. In order to preserve the spatial resolution of the original data set, the smoothed data set is used only to shift the raw data set. Although expression of high-frequency variations have been suppressed in the three-dimensional model, they are present as tonal differences in image form. In effect, the original Landsat image data is overlayed on the digital image topology of the smoothed data set.

Stereo models were produced in this study as stereopairs for viewing with a stereoscope or by viewing as an anaglyph using complementary colour glasses. Stereopairs can be easily displayed on a computer graphic screen as an anaglyph by showing one image as red, and the second image as a combination of both green and blue to produce the cyan image. This technique is useful because most image processing systems have zoom and roam modes that allow for close inspection of subtle and larger scale features.

Psuedo-Stereoscopic Interpretation

The psuedo-stereoscopic enhancement technique is a valuable tool for photographic interpretation, particularly where the detection of edges, or tonal boundaries is important. Standard edge enhancement techniques focus on enhancing the expression of tonal boundaries, or high-frequency features, through high-pass spatial-frequency filtering or by Fourier analysis. These techniques simply enhance the contrast of tonal boundaries in an image. The detection of edges in a monoscopic image by visual interpretation is restricted by the modulation transfer function (MTF) of the human eye (Cornsweet, 1970). The MTF is a measure of the ability of the eyes to detect spatial variations in contrast. Psuedo-stereoscopic enhancement of image data provides a means for displaying variations in image contrast in three-dimensions; edges are detected as abrupt changes in *relief* and also as conventional variations in image brightness.

Fig. III-7 is a stereopair made from a TM band 5 image using the psuedo-stereoscopic enhancement technique. For this study two shifted images were produced to form a stereopair. One image was shifted 4 columns to the right and the other 4 columns to the left, for a total shift of 8 columns. Furthermore, each image of the stereopair was edge enhanced using a 3x3 mean-difference filter (Drury, 1987) to accentuate the relationship between *relief* and tonal boundaries. Viewed stereoscopically the resulting three-dimensional model produces a dramatic effect that clearly displays changes in image brightness as changes in *relief*. Overall, the image displays a varied psuedo-topography (function of the digital image topology) comprised of *rolling hills*, *gulleys*, *depressions*, *ridges*, and *valleys*. *Relief* is expressed as a function of image brightness; bright areas correspond to high tonal *elevations* and the the dark areas correspond to the low tonal *elevations*. Inspection of the original image used in generating the stereopair shows that features with strong topographic expression are associated with sudden changes in *relief* in the stereo model, though the degree and nature of *relief* expression in the stereo model is quite different. The apparent correspondence of some actual topographic features and psuedo-topographic features in the stereo model exist because of strong illumination differences between opposing sides or walls of major landform features (primarily ridges and valleys) in the single image. In

Figure III-7. Psuedo-stereopair of the band 5 subset. Each image has also been edge enhanced using a 3x3 mean-difference filter and contrast stretched with saturation. Stereoscopic relief is a function of image brightness, not topographic relief.

general, topographic features seen in the monoscopic images that are characterized by strong tonal boundaries (significant changes slope magnitude and slope direction) are expressed by corresponding breaks in slope in digital image topology and by sudden changes in *relief* in the stereo model.

The most prominent psuedo-topographic feature (Fig. III-7) is the deep valley containing Butte Creek at the bottom of the image. This feature is a good example and clearly illustrates the factors that contribute to the psuedo-topographic expression of certain features in the image data. The north side of the valley appears extremely steep, while the south side is more gentle. This effect is caused by strong differences in the illumination of the actual topography and in the different reflectance characteristics of the surface materials. The north side of the valley appears very bright, the result of direct illumination and high reflectance characteristics of altered rocks in the area. On the other hand, the south side of the valley is poorly illuminated and the absence of large outcrops of bright reflectors result in low image brightness. The harsh image contrast between the opposing sides of the valley results in considerable *relief* displacement in the stereo model.

Lineaments visible in the original monoscopic image are recognizable as very distinct linear psuedo-topographic features in the stereo model. Most lineaments are clearly seen in the stereo model as small ridge-like or valley-like features. Two distinct lineaments are seen trending NNE, bisecting Butte Creek, and appear as valleys in the lower part of the stereo model. Projecting these lineaments north they become a series of discontinuous curvalinear gullies and ridges in the upper right part of the stereo model. Subtle and questionable lineaments difficult to detect in the original image are more detectable in the stereo model because of the additional factor of *relief* displacement. For example, a group of subtle lineaments trending east-west and located above small ponds in the center of the image are seen as small cliff-like features. The perception of changes in image brightness with changes in *relief* is believed to be a valuable addition to the conventional methods used in the visual interpretation of single images.

NON-TOPOGRAPHIC HILLSHADING

Cartographic Hillshading

Another approach to enhancement that involves the manipulation of image tones can be accomplished through the use of cartographic computer hillshading models. These techniques were developed to simulate the solar shading of digital elevation models (DEMs) to create the visual impression of topographic form. Horn (1982) comments that of all the techniques available to cartographers for making the form of topography apparent on maps, hillshading has the greatest appeal because it provides the important visual depth cue (shading) and is the most amenable method for providing the immediate perception of surface form. Without shading depth clues visual interpretation of topographic detail in DEMs is not possible. Hillshading also provides a means for exaggerating the expression of topographic relief by the variable placement of an artificial lighting source. These basic principles governing the perception of form in DEMs using computer hillshading is directly transferable to the hillshading of the digital image topologies of image data sets. The following section shows that the planar presentation of hillshaded digital image topologies is a useful technique for the enhancement and detection of image lineaments.

Variable Illumination of Topography

The orientation of the sun, or angle of illumination, is of paramount importance for the enhancement of topographically expressed lineaments. The angle of illumination refers to the position of the sun relative to the area being viewed, and is defined by solar azimuth and solar elevation values. Solar azimuth is the horizontal angle measured clockwise from true north, and solar elevation is the vertical angle measured from the horizon plane. The preferential shadow enhancement of topographic features as a function of the angle of illumination has been discussed and demonstrated thoroughly by

Wise (1968,1969), who illuminated various scales of raised plastic relief models from varying solar azimuths and solar elevation. His experiments showed that topographic lineaments are most strongly illuminated by side illumination, while topographic lineaments parallel to the illumination direction will be suppressed. The enhancement of lineaments by side illumination results because opposing slopes of the topographic feature (eg. ridges and valleys) are differentially illuminated. The strongest enhancement of lineaments occurs when one slope is completely illuminated and the other is completely shadowed. Wise's work indicates that maximum enhancement of lineaments occurs when the light source is aligned within 30 degrees of the orientation of the lineament. The suppression of lineaments occurs when resulting illumination on opposing slopes of the linear topographic feature are relatively equal, thereby effectively masking topographic expression.

Walker and Texler (1977) found that the solar elevation has a greater control over the enhancement of topographic lineaments than does solar azimuth. This condition was found to be true for most azimuthal orientations of the sun, except for illumination directions parallel to topographic features. The elevation of the sun controls the degree to which topographic features of variable relief and steepness are enhanced. Low relief features are enhanced best at low solar angles, while more prominent high relief features are enhanced best at high solar elevations where resulting shadows will not mask significant portions of the landscape.

The interpretation of shadow enhanced imagery for lineament analysis is not a quantitative procedure, but rather a very subjective procedure that is greatly influenced by the effects of variable illumination and interpretation bias (Siegal and Short, 1976). Wise (1968) effectively described topographic lineament analysis as a "subtle mixture of science, art, and self-delusion". Over-zealous identification of lines as geologically significant lineaments combined with image processing techniques that create lines where none exist has created a field of remote sensing research that is viewed with concern by many geologists. Nonetheless, the enhancement and detection of lineaments in satellite images has proven to be a valuable and cost-effective tool for structural analysis, especially in reconnaissance investigations for mineral resources.

The Non-Topographic Hillshading Technique

Hillshading of the digital image topology is presented as a method for enhancing the expression of linear psuedo-topographic features (contunuous linear breaks in slope in the digital image topology), and employs the basic principles used in the lineament detection technique involving the illumination of raised plastic relief models presented by Wise (1968,1969). The digital image topology is treated as an actual topography and is artificially illuminated by a single light source using a cartographic hillshading procedure. This technique enhances topographic lineaments not by shadow enhancement but by illumination differences. This approach has the advantage of not masking portions of the image by cast shadows. The non-topographic hillshading of the digital image data is presented as an alternative but more flexible technique for edge enhancement as compared to conventional spatial filtering techniques.

The artifical illumination, or hillshading, of image data in this study was done using a Lambertian reflectance model. The model is based on the assumption that the radiation received on a slope facet is reflected equally in all directions (diffuse reflector), and that there is no absorption of incident radiation (albedo=1). The basis for this transformation is the calculation of a hypothetical intensity of solar radiation for each pixel location in the image data set. The modeling of relative radiance is dependent on two geometric surface measures, slope magnitude and slope azimuth. Both of these measures are first derivative components and can be calculated using finite differences.

The first derivative measure of slope magnitude describes the maximum rate of change in brightness or slope of each pixel in the digital image topology. The first derivative in both the row and column directions are first obtained and the slope magnitude is then calculated from the vector cross products of the two directional derivatives. A 3x3 neighborhood (see Fig. III-8) is used to calculate the directional derivatives. The calculations are after Eyton (1988) and are shown below;

$\text{Slope X} = [Z(2,3) - Z(2,1)],$

$\text{Slope Y} = [Z(3,2) - Z(1,2)],$

$\text{Slope Magnitude} = [(\text{Slope X})^2 + (\text{Slope Y})^2]^{1/2}.$

The slope magnitude values calculated are psuedo-slopes in that only the difference in brightness (rise) values are calculated and the distance between pixel centres (run) are not used in the above calculations. Slope magnitude values (tangent units), however, are scaled so that the majority of the slope values fall into a reasonable slope range; this is user defined. The down slope direction or azimuth of the slope magnitude is determined from the directional derivatives. The local angle O_s between the slope magnitude vector and the horizontal vector component is calculated as follows;

$$O_s = \text{Cos}^{-1}\left(\text{Slope X} \,/\, [(\text{Slope X})^2 + (\text{Slope Y})^2]^{1/2}\right).$$

The local angle is converted to azimuth using the rules given in table III-1.

Hillshading brightness values were calculated using a Lambertian radiance equation derived by Donker and Meijerink (1977) shown below (see Fig. III-9);

$$R = \text{COS}(A_f - A_s)\ \text{COS}\ E_f\ \text{COS}\ E_s + \text{SIN}\ E_f\ \text{SIN}\ E_s, \qquad (1.0)$$

where

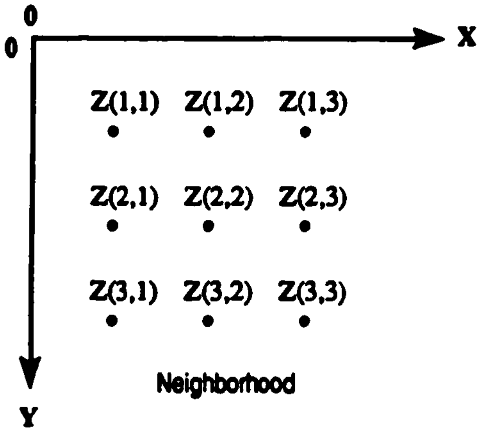
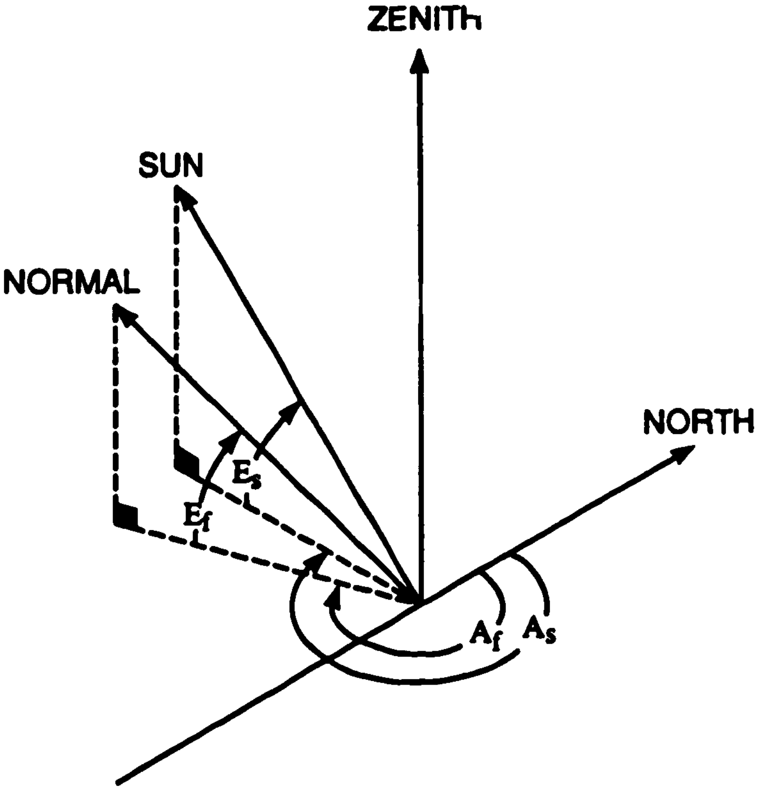


Figure III-8. The 3x3 neighborhood (after Eyton, 1988).

Table III-1. Conversion of Local Angle to Slope Azimuths

	Slope Sign	
Slope Azimuth	Slope X	Slope Y
$270^\circ + 0_S$	+	+
$270^\circ - 0_S$	+	-
$90^\circ + 0_S$	-	-
$90^\circ - 0_S$	-	+

Source: after Eyton, 1988



A_f = azimuth of slope facet

A_s = azimuth of sun

E_f = elevation of the normal to slope facet

E_s = elevation of sun

Figure III-9 Diagram for calculating the relative radiance of a slope facet (after Eyton, 1988).

R = relative radiance (0.0-1.0),

A_f = azimuth of slope facet,

A_s = azimuth of sun,

E_f = elevation of normal to the slope facet,

= 90 degrees-slope magnitude (in degrees),

E_s = elevation of sun.

Hillshading versus Directional Filtering

Hillshading is simply an extension of the conventional directional first-derivative spatial-frequency filtering technique. Directional filtering in the spatial domain is accomplished by determining the brightness gradient, or first derivative, of an image in a particular direction. This is most commonly done by convolution with a square matrix of differentially weighted cells arranged in a specific manner to calculate the brightness variations in a desired direction. A review of the various convolution kernels commonly used in directional filtering is given by Levine (1985).

A directionally filtered image can appear as shaded topography when the output slope components are scaled properly. The result of directional filtering in the spatial domain can be either positive or negative. Positive values represent slope components facing toward the filter pass direction, while negative values represent slope components facing away from the filter pass direction. Drury (1987) produced an image simulating shaded topography of digital aeromagnetic data by rescaling positive values between 128-255 and negative values between 0-128. Chavez et al. (1977), using Landsat MSS data, also produced the illusion of an illuminated topography by adding a constant of 127 to each slope component, and then linearly stretching minimum and maximum values equidistant from the midrange value. Both of the above rescaling methods result in the impression of a topography illuminated by an artificial light source; relatively flat slopes appear as middle gray, positive slope components are highly illuminated, and negative slope components appear shaded.

Hillshading differs from first-derivative filtering in that it incorporates a specified solar elevation for modifying the expression of the directional gradient and is expressed as relative radiance (scaled 0-1). Edges in a standard gradient image are enhanced by conventional stretching techniques and consequently the ability to selectively enhance edges of differing slope magnitude is not easily accomplished. The integration of the solar elevation with the gradient filter makes possible the preferential enhancement of different slope magnitudes. This point is illustrated in Fig. III-10; a slope of 5 degrees can be enhanced to appear brighter than a slope of 80 degrees by using a solar angle greater than 50 degrees.

The Lambertian relative radiance model behaves as a standard directional first-derivative filter when the solar elevation is set to zero. The original function is shown below;

$$R = \mathrm{COS}(A_f - A_s)\ \mathrm{COS}\ E_f\ \mathrm{COS}\ E_s + \mathrm{SIN}\ E_f\ \mathrm{SIN}\ E_s \qquad (1.0)$$

where

R = relative radiance (scaled 0.0-1.0),

A_f = azimuth of slope facet,

A_s = azimuth of sun,

E_f = elevation of normal to the slope facet,

= 90 degrees-slope magnitude (in degrees),

E_s = elevation of sun.

For a horizontal sun elevation:

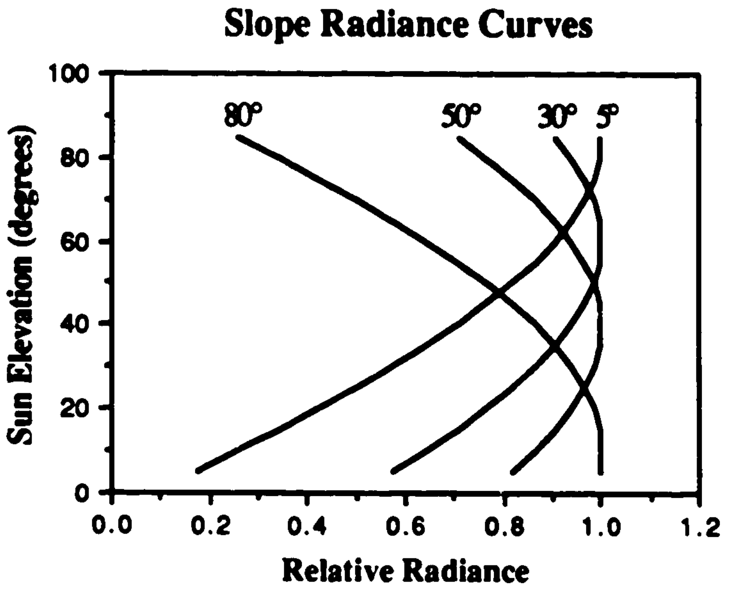


Figure III-10. Slope radiance curves showing the change in relative radiance for a given slope magnitude as a function of solar elevation. The variable position of the solar elevations results in a non-linear changes in relative radiance. The position of the sun can be used for emphasizing desired slope magnitudes, while at the same time subduing the expression of other slope magnitudes.

$\mathrm{SIN}\, E_s = 0,$

and $\mathrm{COS}\, E_s = 1.$

The equation simplifies and becomes;

$R = \mathrm{COS}(A_f - A_s)\, \mathrm{COS}\, E_f.$

The application of this equation produces a radiance data set that is a function of the slope magnitude and the slope direction relative to a specified solar azimuth (or filter direction). In this case the Lambertian radiance model calculates the relative slope magnitude in a particular direction. The following sections demonstrate the value of employing a user defined solar azimuth, and the importance of selecting an appropriate solar elevation as a means for emphasizing desired spatial features in the digital image topology.

Lineament Analysis: Variable Solar Azimuth

The enhancement or suppression of psuedo-topographic features, inherent in the digital image topology of the TM data, due to variable solar azimuth is demonstrated in Fig. III-11. For all four solar azimuths the solar elevation was held constant at 30 degrees. In general the hillshaded digital image topology can be described as a low *relief* terrain; lineaments are seen as distinct variations in illumination intensity, the result of differential illumination of opposite sides of ridges or valleys in the digital image topology. Some lineaments appear in all four images, although their tonal expression increases or decreases according to the angular relationship of the lineaments to the illumination direction. The majority of the lineaments, however, are only detectable in two and sometimes three of the four images. Lineaments oriented at angles roughly perpendicular (within 45 degrees) to the lighting source were found to be enhanced most effectively. This differs from the optimum illumination angle (within 30 degrees of

Figure III-11. Hillshaded images of the band 5 subset showing different solar azimuth orientations (solar elevation held constant at 30 degrees). (a) 315 degrees, (b) 45 degrees, (c) 135 degrees, (d) 225 degrees.

lineament orientation) that Wise (1968, 1969) found for maximum shadow enhancement of topographic lineaments. This difference results because the hillshading technique does not cast shadows; for example, a valley illuminated perpendicular to a light source will produce a shaded wall and an illuminated wall. Using shadow enhancement this same situation might result in cast shadows falling on the sun-facing side of the valley, resulting in suppression of the topographic feature. As well, the effect of the direction of illumination is easily seen on the perception of depth in these images. Images that have opposite sun orientations display an inverted topography relative to each other.

The display of spatial information in the digital image topology as a hillshaded model is also potentially valuable for detecting very subtle lineaments masked by spectral detail in the original image. These type of lineaments generally occur in a very narrow range of solar azimuth orientations and disappear completely outside this range. Subtle lineaments of this type are highly suspect and may represent spurious artifacts created by the program, and therefore should be approached with caution by interpreters, although they may warrant further investigation.

Lineament Analysis: Variable Solar Elevation

The effect of varying the solar elevation on the enhancement of topographic lineaments is shown in Fig. III-12. Extremely low solar angles (Fig. III-12a) produce relatively dark images that are difficult to interpret and mask the form of the image topology. At low solar angles virtually all lineaments, with slopes facing toward the artifical light source, will be illuminated. Very noisy features in the image data, corresponding to regions of varying slopes in the digital image topology, will appear as a series of very bright but narrow lines in the hillshaded image when slopes face the direction of illumination. Smoother features, having less variation in slopes in the digital image topology, will be less bright but appear broader in expression. However, not all

Figure III-12. Hillshaded images of the band 5 subset showing different solar elevation angles (solar azimuth held constant at 315 degrees). (a) 5 degrees, (b) 30 degrees, (c) 50 degrees, (d) 80 degrees.

linear topographic features at roughly perpendicular angles to the direction of illumination will be enhanced. Major topographic lineaments trending NNE in the original image (Fig. III-2) are not visible in the hillshaded image (Fig. III-12a) created using a low solar elevation. This occurs because these lineaments are defined by a break in slope facing SE, and therefore are not illuminated and are lost in the dark background of the image. Overall, lineaments are not easily distinguished in this image.

Fig. III-12b and Fig. III-12c show successively higher solar elevations. Both images give a strong impression of shaded topography and most lineaments present in the original are easily seen, and are clearly enhanced. The higher solar angle has effectively subdued much of the very low *relief* psuedo-topography resulting in a smoother and more interpretable image. Lineaments for the most part are seen as either bright or dark features, and are easily detected against the overall middle grey background of the image. The NNE trending lineaments are now visible because the overall image background has increased in brightness relative to the poorly illuminated lineaments. For most applications solar elevations between 30-50 degrees seem to be most effective in isolating and detecting lineaments that may be geologically significant.

At extremely high solar elevations all but the steepest slopes in the digital image topology are illuminated. Fig. III-12d shows that the overall image is highly illuminated, and is dissected by distinct lineaments representing very steep slope facets in the digital image topology. Comparison of Fig. III-12d and Fig. III-2 show the prominent lineaments detected in this hillshaded image correspond to major topographic features, primarily deep valleys, steep ridges, and north facing cirques. In essence, extreme solar elevations (75-90 degrees) produce inverted slope magnitude images, which are produced with less effort by rescaling the slope magnitude data set for display in image form. For most applications extreme solar angles are not desirable in hillshading because the benefit of viewing a topology from a unique perspective has been lost; the technique is no longer directional.

Edge enhancement

Hillshaded images of Landsat data provide a valuable means for enhancing and detecting edges in the digital image topology. However, grey tones can no longer be related to surface materials and therefore a valuable component of image interpretation will be lost. A simple method is proposed whereby the radiance values of a hillshaded image are used to edge enhance the original image. The edge components of the relative radiance data set are acquired by thresholding. Interactive contrast stretching is used to estimate the proportion of the gray level distribution of a hillshaded image that contains the desired edge information. This proportion is added as a fraction to each relative radiance value (an upper saturation value of one is used), producing a clipped relative radiance data set. Edge enhancement is accomplished by multiplying thresholded relative radiance values (scaled between 0.0-1.0) by the corresponding DN value of the original data set. Essentially a hillshaded overlay has been added to the original image. Edges in the resulting image are enhanced by variable amounts of shade that are a function of the user selected solar elevation. Fig. III-13 is a colour composite that has been edge enhanced using the non-topographic hillshading technique. Each band was individually edge enhanced using the above procedures before compositing. Comparison of Fig. III-13 with Fig. III-5 shows that the edges in the enhanced composite are sharper and more detectable than in the original composite.

Figure III-13. Edge enhanced colour composite with bands 5,4, and 3 coloured red, green, and blue respectively. Each band was edge enhanced using the non-topographic hillshading technique with a slope azimuth of 315 degrees and a sun elevation of 40 degrees. Edges from each hillshaded image were then extracted and used to edge enhance their respective bands before compositing.

SUMMARY

The perception and enhancement of visual depth cues in digital imagery has been examined as an important factor in image interpretation. Shading depth clues resulting from illumination of actual topography by the sun and by the artificial illumination of the digital image topology were shown to be valuable for the enhancement and visual detection of image lineaments. Three techniques were presented for altering and enhancing the perception of lineaments in monoscopic digital images.

The first technique focused on the correction of topographically inverted images and is based on the principles of perceiving depth from shading. The human visual system, in an effort to recover an impression of depth in monoscopic images, unconsciously assimilates the light and shade patterns of an entire image. For reasons not fully understood the human brain usually assumes a single illumination source from the top (north) of a monoscopic image. In images where inversion of topography confuses and confounds visual interpretation simple inversion of image grey scale has been found to be an effective technique for producing an image displaying proper topographic perspective.

The technique of psuedo-stereoscopic enhancement, presented in the second section of the paper, was developed to exploit the stereoptic capabilities of the human visual system. The basis for this technique is the concept that spatial features visible in the digital image topology (a three-dimensional representation of image brightness) provide valuable visual clues that aid in the interpretation of tonal lineaments.
Psuedo-stereoscopic enhancement is used to induce parallax into an image as a function of its own digital image topology. This technique does not produce a stereo model of real world topography, but results in a psuedo-topography in which changes in grey tones are also accompanied by corresponding changes in perceived brightness *relief*. Interpretation of images as stereo models showed that this technique was especially

useful for visually detecting subtle lineaments that would be difficult to identify or possibly missed in conventional image interpretation.

In the last section of the paper cartographic hillshading was presented as a technique for edge detection and enhancement. The digital image brightness data set was again treated as a topology. In Landsat images the tonal differences used in visually identifying lineaments, expressed by surface geometry (topography) and by spectral differences between surface materials, are not always easily detected. Tonal differences, however, are manifested in the digital image topology as breaks in slopes and may be enhanced for visual identification by illumination from a single light source. The shading of the digital image topology provided a necessary depth clue that greatly improved the interpreter's ability for perceiving subtle details in the form of the image topology. User defined solar azimuth and solar elevation were used to preferentially [illegible] topological lineaments. The display of digital image topologies as planar hillshaded images provided a flexible and dynamic means for lineament analysis.

REFERENCES

Arnheim, R., 1974. Art and Visual Perception; University of California Press, 508p.

Batson, R.M., Edwards, K., and Eliason, E.M., 1984. Synthetic stereo and Landsat Pictures; Photogrammetric Engineering and Remote Sensing, vol. 42, no.10, p. 1279-1284.

Chavez, P.S., Jr., Berlin, G.L., and Acosta, A.V., 1977. Computer processing of Landsat MSS digital data for linear enhancements; in Proceedings, second annual William T. Pecora memorial symposium, American Society of Photogrammetry, Falls Church, Va., p. 235-250.

Cornsweet, T.N., 1970. Visual Perception; Academic Press, 430p.

Crippen, R.E., Blom, R.G., and Heyada, J.R., 1988. Directed band ratioing for the retention of perceptually-independent topographic expression in chromaticity enhanced imagery; International Journal of Remote Sensing, vol. 9, no. 4, p. 749-765.

Donker, N.H.W. and Meijerink, A.M.J., 1977. Digital processing of Landsat imagery to produce a maximum impression of terrain ruggedness; ITC Journal, vol. 4, p. 683-703.

Drury, S.A., 1986. Remote sensing of structure in temperate agricultural terrains; Geology Magazine, vol. 123, p. 113-121.

Drury, S.A., 1987. Image Interpretation in Geology; Allen and Unwin, 243p.

Drury, S.A., 1987. Display and enhancement of gridded areomagnetic data of the Solway Basin, International journal of Remote Sensing, vol. 8, no. 10, p. 1433-1444.

Edwards, B., 1979. Drawing on the Right Side of the Brain; J.P. Tarcher, Inc., 207p.

Eyton, J.R., 1984. Raster contouring; Geo-Processing, vol. 2, p. 221-242.

Eyton, J.R., 1988. Colour stereoscopic effect cartography, in review.

Eyton, J.R., 1988. Mapping the differential geometry of digital elevation models; unpublished manuscript, Department of Geography, University of Alberta, Edmonton, Alberta.

Gillespie, A.R., Kahle, A.B., and Walker, R.E., 1986. Color enhancement of highly correlated images. I. Decorrelation and HSI contrast stretches; Remote Sensing of Environment, vol. 20, p. 209-235.

Horn, B.K.P., 1982. Hillshading and the reflectance map; Geo-Processing, vol. 2, p. 65-146.

Levine, M.D., 1985. Vision in Man and Machine; McGraw-Hill Book Company, 574p.

Lueder, D.R., 1959. Aerial Photographic Interpretation Principles and Applications; McGraw-Hill Book Company, Inc., 462p.

MacCurdy, E., 1938. The Notebooks of Leonardo Da Vinci (vol. 2); Reynal and Hitcock, 640p.

Ramanchandran, V.S., 1988. Percieving shape from shading; Scientific American, August, p. 76-83.

Ramanchandran, V.S., 1988. Perception of shape from shading; Nature, vol. 331, no. 6152, p. 133-166.

Robinson, A.H., Sale, R.D., Morrison, J.L., and Muehreke, P.C., 1984. Elements of Cartography; John Wiley and Sons, 544p.

Sabins, F.F., Jr., 1987. Remote Sensing Principles and Techniques; W.H. Freeman and Company, 449p.

Siegal, B.S. and Short, N.M., 1977. Significance of operator variations and the angle of illumination in lineament analysis on synoptic images; Modern Geology, vol. 6, p. 75-85.

Tator, B.A., 1960. Manual of Photographic Interpretation (R.N. Colwell, editor); American Society of Photogrammetry, 868p.

Todd, J.T. and Mingolla, E., 1983. Perception of surface curvature and direction illumination from patterns of shading; Journal of Experimental Psychology: Human Perception and Performance. vol. 9, no.4, p. 583-595.

Walker, P.M. and Trexler, D.T., 1977. Low sun-angle photography; Photogrammetric Engineering and Remote Sensing, vol. 43, no.4, p.493-505.

Wilson, J.G., 1985. Remote sensing for exploration geology: geodermatology, geomorphology, or both? in Proceedings of the International Symposium on Remote Sensing of Environment 4th Thematic Conference, Remote Sensing for Exploration Geology (Ann Arbor: ERIM), p. 195-203.

Wise, D.U., 1968. Regional and sub-continental sized fracture systems detectable by topographic shadow techniques; in Proceedings of the Conference on Research in Tectonics, Geological Survey, Canada, GSE paper 68-52, p. 175-198.

Wise, D.U., 1969. Psuedo-radar topographic shadowing for detection of sub-continental sized fracture systems; in Proceedings of the Sixth International Symposium on Remote Sensing of Environment, University of Michigan Press, p. 603-615.

Woodham, R.J., 1981. Analyzing images of curved surfaces; Artificial Intelligence, vol. 17, p. 117-140.

Yonas, A., Kuskowski, M., and Sterfels, S., 1979. The role of frames of reference in the development of responsiveness to shading information; Child Development, vol. 50, no.2, p. 493-500.

IV. GENERAL DISCUSSION AND CONCLUSIONS

The two papers in this thesis, "Enhanced Landsat Thematic Mapper Imagery for Exploration Geology in the Wheaton District, Southern Yukon", and "The Perception and Enhancement of Depth in Monoscopic Remotely Sensed Images", were both focused on the enhancement of imagery for visual interpretation. The first paper involved the application of existing techniques and the second introduced new techniques. Although both studies were separate and stand alone, they used the same study site and were concerned with the extraction of geological information and in particular the identification of lineaments.

In the first paper only current and commonly used image processing techniques were used to demonstrate the usefulness of remote sensing for mineral exploration. Although the first study presented no new approaches, and therefore was applied research, it satisfied several purposes:

1. Met a personal objective of the author in his graduate studies; namely that of initiating, planning, funding, and conducting a field oriented remote sensing study in Canada's north.
2. Significant new fractures were mapped in the Wheaton District that were previously not suspected, and images were generated for the district that showed areas of potential hydrothermal alterations.
3. Communication with small exploration companies and individuals during the field studies provided an avenue for directly and honestly presenting the usefulness and limitations of remote sensing for mineral exploration. The exchange of ideas with workers in the field provided the author with invaluable experience that can only benefit my work in the future.
4. This paper is being published in *Yukon Geology* where it is hoped that it will serve

as a basic reference guide for those interested in using remote sensing as part of their exploration strategy.

The second paper was an attempt at developmental research. In this paper the focus was on two areas; the perception of depth in a monoscopic image, and the development of enhancement techniques for exploiting the human visual system's ability for detecting topological detail in digital image data sets. The role of the depth cues for realizing image information (particularly lineaments) was shown to be critical and three techniques were presented that are based on simple principles of the perception of depth; 1. the correction of topographically inverted images by grey scale reversal, 2. The psuedo-stereoscopic enhancement of imagery for displaying changes in grey tones by corresponding changes in brightness *relief*, and 3. Cartographic hill shading of image data sets to detect edges.

The principles governing the perception of depth in monoscopic images are still relatively new and the application of these principles in comprehending the role of the human visual system in image interpretation is even less well understood. In this paper an attempt has been made to apply some of the basic principles governing the perception of depth of simple objects to the complex world of monoscopic images, and to enhance certain image characteristics that exploit the brain's ability for perceiving depth. This paper provides a basic framework for a better understanding of the visualization of digital image data.

Overall, this thesis moved from a general application of existing techniques in the first paper, to the development of specific techniques in the second paper. The first paper was a general study, in that only commonly used remote sensing techniques were employed. The emphasis of this study was the application of these techniques to a "real world" problem, i.e. exploration geology. Because the first study was field intensive, valuable experience was gained by the author in understanding the limitations and difficulties in conducting field oriented research. The second paper, on the otherhand, focused on applying the basic principles of the perception of depth that were discovered while conducting the first study. The role of the perception of depth, combined with techniques commonly used in computer cartography, formed the basis for the development of techniques used to enhance tonal features for visual interpretation. In the end, this thesis provided the author with an opportunity for demonstrating the application of an existing technology and for the development of new techniques that should useful to others.