THE ANALYSIS AND INTERPRETATION OF SPECTRAL REFLECTANCE SIGNATURES FROM ROCK GLACIERS

By

SUSAN MARY BERTA

Bachelor of Arts

University of Michigan - Flint

Flint, Michigan

1979

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
July, 1982

THE ANALYSIS AND INTERPRETATION OF

SPECTRAL REFLECTANCE SIGNATURES

FROM ROCK GLACIERS

Thesis Approved:

____
Thesis Adviser

____

____

____

____
Dean of Graduate College

ACKNOWLEDGMENTS

I owe many people a great deal of thanks for their help and friendship over the past two years. The following people are especially noted for their contributions of time and effort put forth towards the completion of my degree.

I would like to express my sincere appreciation to my major adviser, Dr. John D. Vitek, for his guidance, assistance, and most of all his patience throughout this study. His interest in and enthusiasm for the subject made the task a little easier. I would also like to thank him for initially encouraging me to come to Oklahoma State University and for allowing me to be involved in his research.

Appreciation is also expressed to the other committee members, Dr. Stephen J. Walsh, Dr. Richard D. Hecock, and Dr. John A. Harrington, for their invaluable assistance in the preparation of the final manuscript. Special thanks go to Dr. Walsh for allowing me to use the equipment at the Center for Applications of Remote Sensing (CARS) to process and interpret the Landsat data. I am very grateful that he afforded me the opportunity to study a topic of great personal interest.

I especially thank Mark Gregory for all of his help and support over the past two years. His advice, criticism, and reassurance has helped save this "Flintoid" from depression. Moreover, I thank him for, after all is typed and done, still being interested in me and what I have to say.

Most of all, I would like to thank my family. Their love and support has helped ease the added pressure of being so far away from home. A special thanks goes to my Mother, who for twenty-five years, has provided a constant source of love and help to me. I would like to thank her for never being too overbearing and always being too proud of me.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Purpose of Study

The Earth is a highly diversified surface which shows great complexity and variability in topographic relief and material composition. People continue to study the earth's surface in an attempt to better understand its origin and the processes which govern its evolution. Presently, many earth surface studies utilize remote sensing for data acquisition. The purpose of this study is to assess the feasibility of investigating alpine geomorphic phenomena through the use of Landsat digital data and computer enhancement techniques.

Two pattern recognition approaches may be utilized to identify alpine landforms with Landsat digital data. Pattern recognition involves the interpretation of features, such as rock glaciers, based upon their representative spectral characteristics. One interpretive approach identifies a spectral value or set of spectral values which uniquely represent rock glaciers on Landsat digital data. Values representative of rock glaciers would account for variations in size, orientation, and/or surface texture and composition throughout the study area. Collectively, a set of spectral signatures may be identified which only represent rock glaciers.

The second approach involves identifying a unique arrangement or pattern of spectral signatures which represent rock glaciers on Landsat digital data. The range of spectral values found within rock glaciers may vary from one rock glacier to another but may be arranged in a pattern indicative only of rock glaciers. This present investigation will utilize the first approach as a means of identifying spectral signatures representative of rock glaciers.

Remote Sensing

The science and art of remote sensing permits the collection of information about an object, area, or phenomenon by a device that is not in contact with the subject under observation. More specifically, remote sensing refers to methods that employ electromagnetic energy as a means for detecting and measuring specific characteristics (Sabins, 1978). Remotely sensed data, in general, consist of wavelength-intensity information which record electromagnetic radiation either reflected from or emitted by an object at specific wavelengths and intensities. This definition excludes electrical, magnetic, and gravity surveys which describe force fields, but rather includes several types of electromagnetic radiation such as light (visible), heat (thermal infrared), and radio and microwaves.

The most common form of remote sensing data is aerial photography which employs the visual and near infrared portions of the electromagnetic spectrum. Black and white aerial photography first originated in the 1850's. In World War II, specialized cameras for aerial surveillance were developed for use in terrain studies. In the 1960's, further technological developments enabled imagery to be acquired at other wavelengths, including thermal infrared and microwave. Today, aircraft and satellites are the common platforms from which remote sensing observations are made. Scientific investigations presently involve the detection, mapping, and monitoring of the planet's natural resources. A primary vehicle for accomplishing this task is the Landsat satellite.

Landsat

The National Aeronautics and Space Administration (NASA) with the U. S. Department of Interior developed a program in 1967 to launch unmanned satellites specifically designed to acquire data about earth resources on a systematic, repetitive, medium resolution, multispectral basis (Lillesand and Kieffer, 1979). Landsat-1, formerly named ERTS-1 (launched July 23, 1972), Landsat-2 (launched January 22, 1975), and Landsat-3 (launched March 5, 1978) are unmanned satellites that orbit the earth collecting remotely sensed data.

These satellites scan the earth in a circular, near-polar orbit at an altitude varying between 880 km and 940 km passing within nine degrees of the North and South Poles. They circle the earth once every 103 minutes resulting in 14 orbits per day with repeat coverage over any given area every 18 days. A sun-synchronous orbit allows the satellites to keep precise pace with the sun's westward progress as the earth rotates. This ensures consistant sun illumination conditions between orbital passes for similar latitudinal locations. The Landsat platforms contain two primary sensing systems, the Return Beam Vidicon Camera (RBV) and the Multispectral Scanner (MSS). The research summarized here focuses on the use of data recorded by the Landsat MSS.

In general, multispectral scanners can sense reflected and emitted energy from ground objects simultaneously with the spectral bands ranging from ultraviolet wavelengths through the visible, reflected infrared (IR), and thermal portions of the spectrum (Siegal and Gillespie, 1980). The Landsat MSS detects reflected solar energy in four wavelengths, or spectral bands: two in the visible spectrum at 0.5 to 0.6 um (green) and 0.6 to 0.7 um (red), and two in the near infrared at 0.7 to 0.8 um and 0.8 to 1.1 um. These bands are designated 4, 5, 6, and 7, respectively, and are recorded simultaneously by the detector built into the MSS receiver.

The MSS onboard Landsat is a line scanner incorporating an oscillating mirror that continuously scans a series of swaths perpendicular to the orbital path. The active scan traces six rows of data at a time in a west-to-east direction, returns to its starting position in the inactive mode, and then begins the next active scan. This sequence continues recording data as long as the MSS is programmed to operate. The result is a set of recorded data consisting of scan lines (rows) and elements (columns) of reflectance values.

The data utilized in this research consists of a portion of a Landsat scene. A scene covers a 185 km by 185 km area and is comprised of individually recorded radiance values with a ground resolution cell size of 79 meters by 57 meters. Radiance values range from 0 to 127 for bands 4, 5, and 6, and 0 to 63 for band 7, where 0 represents an amount of reflected energy too small to be measured by the detector and 127 or 63 represent total saturation or maximum reflected energy.

Radiance information, telemetered from the satellite, is radiometrically and geometrically corrected before being stored in digital form on a Landsat Computer Compatible Tape (CCT). The digital data are used to create imagery of the earth's surface and are in a format which facilitates efficient data manipulation through computer algorithms. This research investigation is based upon analysis of Landsat CCT data and the employment of specific computer enhancement techniques.

Geomorphology

Applications of Landsat data are utilized in many scientific fields such as: agriculture, civil engineering, climatology, forestry, geography, geology, geophysics, land resources analysis, land use planning, oceanography, and water resources analysis (Lintz and Simonett, 1976). Analyses utilizing Landsat data, however, have been limited in geomorphological research.

Geomorphology encompasses the scientific analysis of the forms, processes, and spatial distribution of landforms. Landforms include a vast array of features that, taken together, make up the surface of the earth. They include all broad features such as plains, plateaus, and mountains as well as all minor features such as hills, valleys, slopes, canyons, and alluvial fans (American Geological Institute, 1976).

In the past, utilization of Landsat data for geomorphic research has been limited because of commonly weak correlations between geomorphological units and land cover or land use. Land cover, from which land use can be derived, is the feature most directly recorded by the Landsat MSS. Approximate correspondence between vegetation or land cover patterns with geomorphic units must be obtained if reliable results are to be expected (Verstappen, 1977). These factors limit applicability of Landsat multispectral data in geomorphology. Landform identification is also hindered because, oftentimes, the feature is comprised of materials that are ubiquitous and common to the area. In this case, reflectance values arranged in a fashion distinctly representative of rock glaciers must be found. If, however, certain geomorphic phenomena have a characteristic surface texture, size, and orientation, a specific spectral signature of reflectance may exist which in turn may be detected through an analysis of Landsat MSS data. The following investigation relies on computer enhancement techniques in the analysis of Landsat digital data in an attempt to establish specific reflectance characteristics for a particular geomorphological unit.

Rock Glaciers

Rock glaciers have been selected for investigation because they are large, virtually non-vegetated alpine landforms (Figure 1). They are masses of unsorted talus debris having glacier shapes and usually spreading down valley from cirques. They differ from alpine glaciers in that no perennial surface ice is visible on rock glaciers. The debris-covered surfaces usually exhibit ridges, furrows, and lobes indicating that flow is or has taken place in the rock. They vary in size, shape, composition, and texture.

The three different forms of rock glaciers, tongue-shaped, spatulate, and lobate (Wahrhaftig and Cox, 1959), consist of rock fragments with internal ice. A tongue-shaped rock glacier can be recognized by its many ridges and furrows which sprawl across this feature. A spatulate rock

Figure 1. Rock Glaciers of the Blanca Massif

glacier is a tongue-shaped rock glacier that spreads laterally across wide valley floors. The third form, the lobate rock glacier, has greater breadth than length and develops below alluvial and avalanche talus along valley walls.

Two different ice characteristics exist in rock glaciers: buried glacial ice (debris-covered glaciers), called ice-cored rock glaciers, and interstitial ice, known as ice-cemented rock glaciers. Ice-cored rock glaciers are discernable on aerial photographs by their typical depressions between the rock glacier and the headwall cliff; longitudinal, marginal, and central meandering furrows; and collapse pits. Ice-cemented rock glaciers do not ordinarily possess these features (White, 1975). Ice-cored rock glaciers are "composed of relatively clean glacier ice that is mantled by debris," while ice-cemented rock glaciers are "rock glaciers that contain considerable debris cemented by interstitial ice" (Potter, 1972, p. 2037).

Three elements are involved in the development of rock glaciers. First, the rock floor in which the ice and talus are situated must slope in such a way as to enable ice to flow in response to gravity. Second, snow and water must accumulate and later change to ice. And third, the rock debris must come to overlie the ice (Parson, 1979).

Rock glaciers, commonly found on east and southeast-facing slopes, result primarily from topoclimatic factors. The greatest snow accumulations occur in leeward depressions and are preserved by shadows and, in some cases, insulation. The leeward calm which promotes accumulation may also inhibit ablation if wind patterns are favorable and consistent throughout the year. Insulation may be provided by entrained debris, by surficial accumulation of fallen rock, or by talus when snow sifts down into pockets between the rocks (Thompson, 1962). These characteristics commonly aid in the development and maintenance of rock glaciers.

In relation to ice content and activity, rock glaciers can be classified as active, which show an actual movement of downslope creep at an average speed of 15-100 cm/yr; inactive, which no longer show any movement but still contain ice; or fossilized, which are ice-free and have subsequently collapsed (Barsch, 1977).

Although all of the aforementioned rock glacier characteristics can be discerned on aerial photography (Parson, 1979), it has yet to be determined whether or not Landsat MSS digital data may be utilized in the identification and discrimination of rock glaciers. This study, with the aid of computer algorithms, will assess the feasibility of identifying rock glaciers by a spectral signature or set of spectral signatures using Landsat digital data.

Study Area

Located in south-central Colorado, the Blanca Massif is a section of the Sangre de Cristo Mountains that extends from Mosca Pass southward toward La Veta Pass. To the west and south it is bound by the San Luis Valley and to the northeast by Huerfano Park while to the east lies the saddle between the Massif and Slide Mountain. This is an area of extremely rugged topography with four peaks greater than 4,250 meters above mean sea level (Figure 2).

The center and northeast sides of the Massif are drained by the Huerfano River which joins the Arkansas River 65 kilometers east of Pueblo, Colorado. The west side is drained by several streams that disappear in the San Luis Valley. Water on the south and southeast sides of the Massif drain primarily into Ute and Cottonwood Creeks, eventually reaching the Rio Grande River. Vegetation in the study area is the typical Southern Rocky Mountain sequence with alpine associations beginning at approximately 2,750 meters. Throughout most of the area, timberline lies within a few meters (30 meters) of 3,500 meters.

Parson (1979) observed that rock glaciers in this area do not exist below 3,350 meters. This present study is therefore confined to that area above 3,350 meters and thereby covers approximately 83 square kilometers within the Blanca Massif.

The Landsat Computer Compatible Tape (CCT) used in this study was recorded on October 6, 1979. Although this date is not ideal for minimizing sun angle effects (approximate sun azimuth being 48 degrees 13 minutes), it does provide snow-free and cloud-free data for analysis.

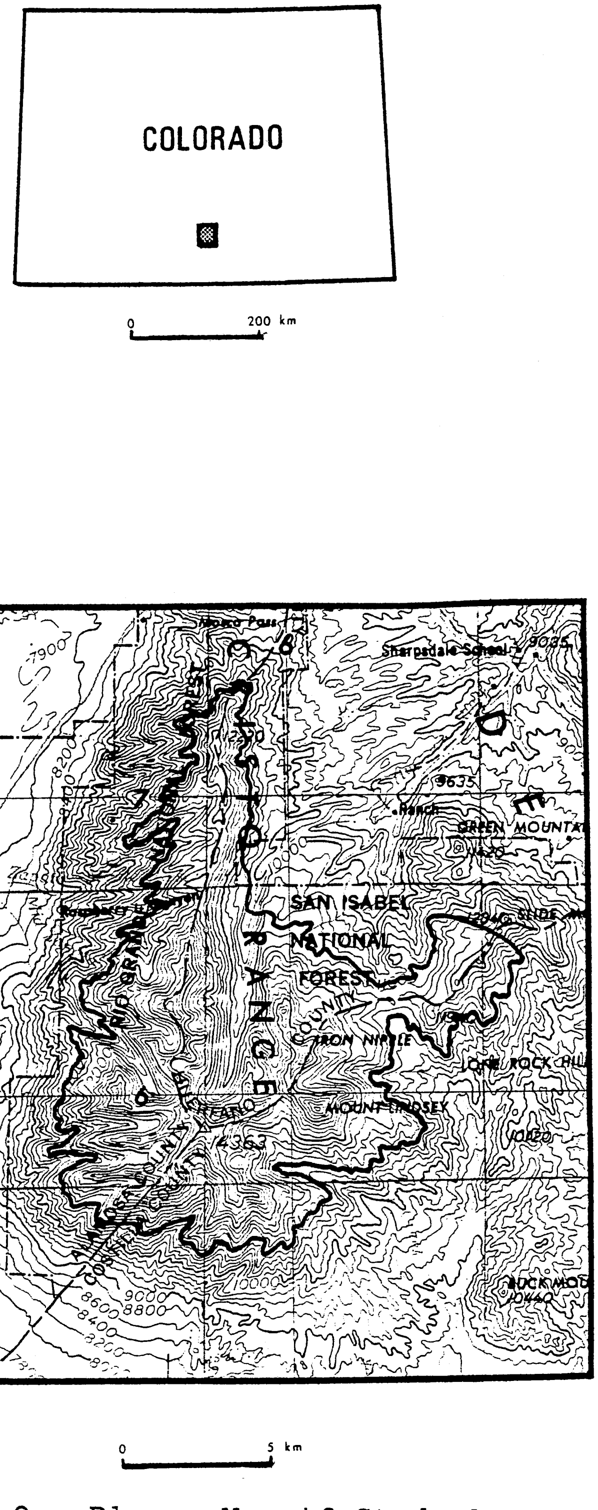

Figure 2. Blanca Massif Study Area

Area Geology

Based on the reconnaissance geology of Johnson (1969), the Blanca Massif consists of granitic metamorphic rocks that have been thrust at a low angle over gently dipping sediments which lie on a Precambrian metamorphic base (Figure 3). The area is comprised of metamorphic rocks such as granodiorite gneiss, hornblende gneiss, amphibolite, metasedimentary schist, and quartzite. Igneous rocks such as hornblende diorites and tertiary volcanics can also be found in this area as well as sedimentary rocks such as those comprising the Minturn Formation (mixed conglomerates, shales, arkose sandstones, and limestones) and the Sangre de Cristo Formation. Quaternary deposits, including moraines and rock glaciers, are also present.

The area is suited to this study of rock glaciers because the rock glaciers represent almost the entire range of forms described in the literature. The rock types, although mineralogically varied, yield the necessary coarse, angular talus for rock glacier development.

Summary

The goal of this study is to assess the feasibility of utilizing Landsat digital data and selected computer algorithms to identify rock glaciers, a specific geomorphic phenomenon. Rock glaciers may possibly be identified on Landsat digital data either by a unique spectral signature or set of signatures associated with rock glaciers or by a

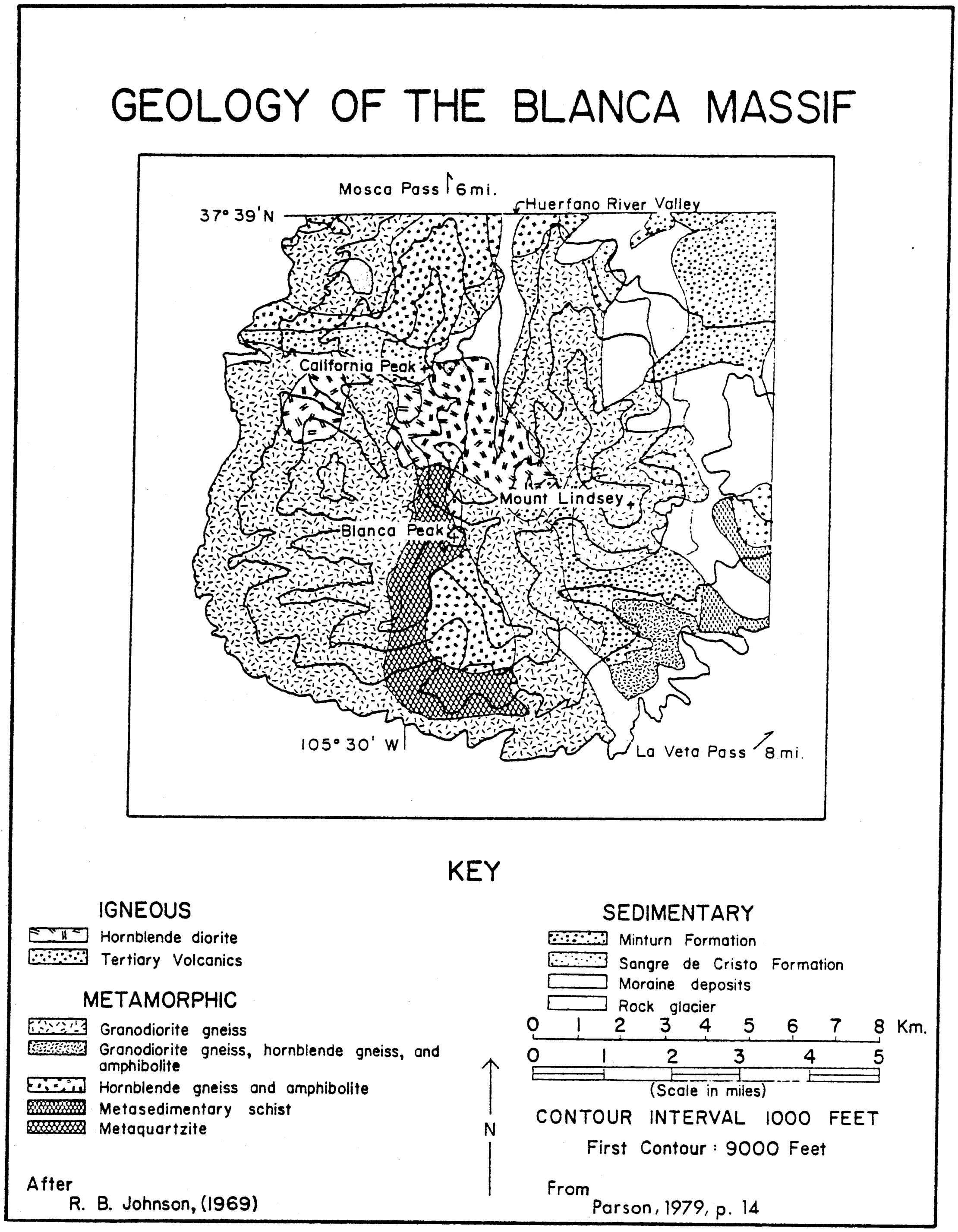

Figure 3. Geology of the Blanca Massif Study Area

pattern of spectral signatures common only to rock glaciers. Computer enhancement techniques were used in this study on Landsat MSS digital data to identify a unique or set of unique spectral signatures characteristic of rock glaciers. The null hypothesis to be tested states that no unique spectral signature or set of spectral signatures may be identified for these relatively large, alpine landforms (size ranges from approximately 2 to 99 hectares) in the Blanca Massif study area. The alternate of this hypothesis is that unique spectral signatures for these rock glaciers can be identified and therefore rock glaciers can be discriminated from the surrounding environment as a unique land cover type. The results of this investigation will indicate the feasibility of utilizing Landsat digital data for discriminating geomorphic phenomena in alpine environments.

CHAPTER II

LITERATURE REVIEW

Introduction

Extensive research has been conducted to understand the development and occurrence of rock glaciers by Outcalt and Benedict (1965), White (1976), and Barsch (1977). Other studies, however, have utilized remotely sensed data for identification of landforms such as rock glaciers with the emphasis placed more on the characteristics of the environments in which these landforms are found.

In the past, large scale black and white aerial photography has been used extensively to aid in rock glacier identification and analysis (Wahrhaftig and Cox, 1959). Osborn (1975) used aerial photographs from 1947 through 1974 to calculate the rate of rock glacier movements in Banff National Park, Alberta, Canada. P. G. White (1979) conducted a study in the San Juan Mountains, Colorado on rock glacier morphometry. He investigated geographic patterns of characteristics which could not be discerned from localized studies. White interpreted 613 rock glaciers for measurement from aerial photographs and topographic maps. Parson (1979) identified 44 rock glaciers in the Blanca Massif study area utilizing black and white aerial photography at an approximate scale of 1:20,000. His interests centered around identifying locational causes for the occurrence of rock glaciers in the landscape and understanding morphological variations as a function of site characteristics. The research in this study utilizes another form of remotely sensed data to identify rock glacier surfaces, that of Landsat MSS data.

Remote Sensing Techniques for Rock Type Discrimination

Since rock glaciers are relatively non-vegetated masses of unsorted talus debris, this investigation will analyze those areas comprised primarily of rock. The successful discrimination of all rock types from the surrounding environment will aid in the identification of sites with rock glaciers. Raines and Lee (1974) evaluated the use of multiband aerial photography for rock discrimination. Over 8600 in situ band reflectance measurements were obtained for sedimentary rocks of the Front Range, Colorado. Statistical analysis of these measurements showed that: (1) band reflectance measurements are not site-specific, (2) only one basic spectral reflectance curve exists for sedimentary rocks, and (3) the natural variation among these rocks is so large that at least 150 measurements per formation are required to select "best" filters. Raines and Lee concluded that because of data acquisition and registration problems, and the lack of significant contrast between sedimentary rock units, this method for rock discrimination is not practical for improving discrimination capabilities for sedimentary rocks.

Acquiring the ability to discriminate all rock types to aid in the location of rock glaciers appears feasible with Landsat MSS data. Salisbury and Hunt (1974) focused their research on Landsat's ability to detect general rock type. The spectra of more than 200 mineral and 150 rock samples were studied to determine the origins of their spectral features and assess the utility of the visible and near-infrared regions for remote sensing of rock types. Conclusions revealed some differences in the spectral behavior of different rock types in the visible and near-infrared spectral regions. They did not recommend that this spectral region be used for mapping rock composition. Instead, this region is best for applications such as: enhancing the visibility of a rock unit with a known and distinctive spectral signature; or enhancing the contrast between rock units; or between rocks and vegetative background. Since the present research calls for separation of all rock areas from vegetative background, Landsat MSS data will provide a sufficient source of data.

Methods to improve the discrimination of rock types with Landsat MSS data are presently being developed. An assessment of filters for discrimination of rock type with Landsat data based on laboratory spectra information was performed on 284 known rock and soil specimens by Hunt and

Salisbury (1978). Band ratio values corresponding to each of the spectral measurements were determined using the four Landsat MSS bands. Based on the derived spectral information in the MSS bands, it was concluded that the ratios could generally be used to discriminate different lithologic units. This spectral information excludes textural, geomorphic, and vegetational effects. Band ratioing is a procedure in which corresponding pixel values from different spectral bands are ratioed together (one band divided by another). An advantage of utilizing band ratioing is that it removes the effects of some sensor radiometric errors and random changes in scene irradiance caused by atmospheric and topographic differences across a scene of data (Slater, 1980).

Another study attempted to discriminate rock and soil types by analysis of digital Landsat MSS data (Podwysocki and others, 1977). A technique known as contrast stretching was applied to the data to provide greater separation among the raw count values. The bands of data were then ratioed, followed by a second contrast stretch procedure. Successful discrimination among igneous, metamorphic, and sedimentary lithologies resulted. Principle component analysis, followed by a contrast stretch of the transformed data also provided good separation of the various lithologies. Canonical analysis produced a more detailed image than the more general principle components, band ratio, or contrast enhancement procedures but involved much more work. They concluded that exact results appeared to be scene-dependent.

Other studies have been conducted to derive rock type information. General geologic mapping techniques utilizing remotely sensed data depend on accurate identification of rock type. A comparison of geologic mapping techniques was conducted by employing Heat Capacity Mapping Mission (HCMM) imagery and Landsat imagery in Northwest Queensland, Australia (Cole and Edmiston, 1980). Landsat, with its greater resolution (79 meters square compared to 700 meters square for HCMM) and four-band range of data (HCMM uses two bands), was found more useful for geologic mapping while HCMM was found to be more suited to drainage studies.

Applications of Landsat MSS data for geologic mapping, therefore, appear plausible. A study performed in Antarctica (Houston and others, 1976) employed Landsat imagery for mapping of geologic units. Brightness contrasts between different rock units were greatest in MSS band 7. Details of flow structure were identified in this band of data which were similar to those found on rock glacier surfaces. The overall study concluded that by dividing band 4 by band 7 (band ratioing) greater contrast between different rock units was possible and resulted in increased accuracy for geologic mapping.

Blodget and others (1975) assessed the applicability of computer classification and/or image enhancement for rock identification in northwestern Saudi Arabia. The selected MSS bands were ratioed and then contrast stretched to enhance spectral image differences. In the ratioing procedure, alternative ratio combinations were used to enhance specific rock classes in different areas. The combination of the ratios of bands 4 to 5, 5 to 6, and 6 to 7 provided the greatest amount of discriminative data. A histogram equalization stretch provided maximum contrast throughout the study area. The three stretched data sets were classified utilizing the principle of maximum likelihood and combined into a color composite image with the initial results indicating that several igneous and sedimentary rock types could be discriminated utilizing this set of procedures.

In a later study, Blodget and others (1978) utilized Landsat MSS digital data and computer enhancement techniques for an area in the southwestern Arabian Shield to improve discrimination of rock classes and for recognition of gossans associated with massive sulphide deposits. The study focused on evaluating image enhancement techniques that would minimize topographic effects. Rock discrimination was found to be best for the following band pairs: ratios 4 to 5, 5 to 6, and 6 to 7. A color composite image was produced for interpretation with information from ratio 4/5 projected through a blue filter, ratio 5/6 through a green filter, and ratio 6/7 projected through a red filter. This set of computer-enhancement programs allowed meaningful discrimination of rock and rock alteration materials to be obtained. Spectral correspondence to rock units mapped at a scale of 1:100,000 from visual interpretation had greater than 80 percent accuracy. The study area was selected for the variety and extensiveness of its rock outcrops, negligible vegetation, and minimal soil and chemical weathering cover. Conclusions of this study suggested that, with modifications and improvements in digital enhancement/transformation techniques and/or sensors carried on future satellites, the general techniques would be applicable in other, less arid regions such as south-central Colorado.

Applications of digitally processed Landsat MSS imagery for mineral exploration are based on successful identification of rock type. Processing of enhanced Landsat digital data was used by Lyon (1975) to increase its application in mineral exploration. This was accomplished by producing enhanced images with higher contrast and resolution and by pattern recognition techniques applied by computer analysis of the four-band digital spectra. This study looked at mineral exploration problems in zero vegetation cover (Goldfield, Nevada), mixed cover of pinon pine and juniper (Pine Nut Mountains, Nevada), heavy birch forest (Karasjok, Norway), and full tropical cover (Fifalmin, New Guinea). Findings from the zero vegetative cover study were most relevant to the present research. In the Goldfield study, band ratio and contrast stretch procedures were utilized to identify various mineralogical areas. A ratio of band 5 by band 4 was used to emphasize iron-oxide rich areas which have high ratios in these bands. The ratio procedure distinguished most altered (highly mineralized) rocks from unaltered rocks. The study concluded that no one enhancement technique works all the time and therefore, a group of approaches must be attempted and used. For greatest accuracy in mineral exploration, a geologist, who is personally familiar with the area and problem, is essential for extracting the most information from the Landsat system.

An investigation by Rowan and others (1977) attempted to discriminate hydrothermally altered and unaltered rocks utilizing Landsat MSS imagery. Mineralogical differences between altered rocks and most unaltered rocks in south-central Nevada caused visible and near-infrared (0.45 to 2.4 um) spectral reflectance differences. These differences were used to discriminate broad categories of rocks in multispectral images. The shapes of the 0.45 to 2.4 um spectral curves for the altered and unaltered rocks were distinctly variant. These differences were not apparent in individual MSS bands or color composite MSS images because of the wavelengths and wavelength ranges of the Landsat MSS bands. Techniques were developed to enhance these subtle spectral differences which combined ratios of the MSS bands and contrast stretches. A color-ratio composite for discriminating between altered and unaltered rock areas, as well as among many unaltered rocks, was prepared using diazo color and stretch-ratio image combinations; blue for ratio 4 to 5, yellow for ratio 5 to 6, and magenta for ratio 6 to 7. Field evaluations concluded that approximately 80 percent of the identified alteration areas were correct. The remaining 20 percent could possibly have been identified if the Landsat MSS spectral regions were extended to 2.2 um. The ability to accurately and consistantly distinguish rock characteristics is essential for geomorphic (rock glacier identification) as well as geologic mapping. Landsat MSS data, with the aid of computer enhancement techniques, can provide quality information for geomorphic and geologic applications.

Remote Sensing Techniques for Landform Identification

Remotely sensed data have been used in the identification of a variety of landforms. Schneider and others (1979) utilized enhanced nighttime thermal infrared imagery and digital data from a National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellite to successfully map drainage patterns and landforms in North and South Dakota. Recommendations were made that geomorphologists should become acquainted with the improved thermal infrared data available from the NOAA TIROS-N satellite as well as the NASA HCMM and Landsat-3 Multispectral Scanner.

Utilization of Landsat data in other geomorphic studies has resulted in limited success. Nyberg (1980) attempted to identify avalanche landforms and general geomorphology in mountainous areas utilizing stereoscopic Landsat MSS imagery. He anticipated that stereo viewing of the imagery would increase its potential for applications in geomorphic and geologic studies. Landsat's restricted resolution, limited ability to detect relief displacement, and the problem of obtaining optimum imagery over large areas are present limitations of this data application to the survey and mapping of avalanche landforms in mountainous areas.

The present research involves the use of Landsat digital data and computer enhancement techniques to aid in obtaining more discrete data for geomorphic interpretation. Since Landsat MSS sensors detect only spectral characteristics of surface materials, automatic identification of unique spectral signatures for specific landforms is difficult (Hoffer, 1974). Weak correlations between surface cover type and landform occurrence are common problems associated with landform mapping (Verstappen, 1977). Present computer-aided analysis of spectral data provides a basis from which landform mapping can begin. State-of-the-art analysis techniques require human interpretation for increased accuracy in landform identification. Field knowledge is essential, especially in mountainous environments where circumstances such as shadowing effects must be considered during analysis and interpretation (Hoffer, 1974).

Swain and Davis (1978) suggested that geomorphologic mapping through remote sensing presents a problem to the data analyst related to the nature of geomorphic studies. The objective of their study was to delineate surface landforms in an alpine border area through analysis of spectral reflectance measurements. Botanical, hydrologic, and cultural patterns were inferred from the Landsat MSS data to aid in landform recognition. Results from this study demonstrated that the analysis process, based on spectral information, requires that the interpreter have a sufficient understanding of the local geology. They suggested that future refinements in machine-aided analysis of spatial features will lead to procedures for geologic mapping that require less human intervention than is presently needed.

Utilizing Landsat MSS digital data and several band ratio techniques, Shroder (Personal Communication, 1982) attempted to identify rock glaciers in a study area in Afghanistan. He found that shadows and snow present in some cirques inhibited accurate identification of these landforms. Since field data were not available for this area at the time the Landsat data were recorded, the research effort was terminated. Shroder concluded that rock glacier identification is possible but field data recorded at the time of the Landsat pass are essential for valid results to be obtained.

Summary

Strategies in the present research include the utilization of several computer enhancement techniques on Landsat digital data to aid in rock glacier identification. A series of band ratios are expected to reduce and/or eliminate sun illumination effects and enhance rock discrimination from the surrounding environment. A contrast stretch procedure will maximize discrimination (or distance) between classes, and a maximum likelihood classification procedure will aid in identifying rock areas throughout the study area with similar occurrences of local reflectance. The combined utilization of these enhancement techniques will further aid in recognizing distinct differences between various surface parameters. The distinct surface characteristics of rock glaciers, therefore, will then be represented on the enhanced Landsat digital data by a signature or set of spectral signatures unique to rock glaciers. The precise methods of data analysis, results, and conclusions of this study will be discussed in the following chapters.

CHAPTER III

METHODS OF ANALYSIS

Introduction

The feasibility of utilizing Landsat MSS digital data to detect alpine landforms can be investigated by assessing Landsat's ability to discriminate rock glaciers, one of the largest and most distinct alpine landforms. This chapter contains a detailed description of the computer processing procedures and computer enhancement techniques applied to Landsat data to detect rock glaciers in the Blanca Massif study area.

Since no one or any set of enhancement techniques works all the time for all imaged areas (Goetz and Rowan, 1981), several different band ratio combinations were tested for their effectiveness in identifying rock glaciers. The methods of analysis reported here provide data from which to assess Landsat's capability for detecting rock glaciers on the Blanca Massif by identifying spectral signatures uniquely representative of rock glaciers.

Aerial Photographic Identification

The initial task of this study was to establish the boundaries of the study area. An investigation with black and white aerial photography by Parson (1979) identified 44 rock glaciers on the Blanca Massif above 3,350 meters. A similar interpretative search of aerial photographs was conducted to check Parson's findings for applicability in this research. Stereographic pairs of black and white aerial photographs at a scale of 1:20,000 (September 22, 1955) were used in this study to distinguish rock glaciers from features that appeared similar, such as talus slopes, protalus ramparts, avalanche chutes, and moraines (see Appendix).

Rock glaciers need to be distinguished from talus slopes because the contact between them defines the head of the rock glacier and the toe of the talus slope. Parson (1979) determined that talus slopes are much steeper (mean slope equal to 33.6 degrees) than the upper surfaces of rock glaciers (mean slope equals 9.6 degrees) and the fronts (toes) of rock glaciers (mean slope equal to 37.2 degrees) are in turn steeper than talus slopes. The identification of the contact line was aided, in most cases, by the presence of a slight depression at the back of the rock glaciers. Differences in tone and texture on the aerial photographs were also indicators used for establishing the contact line boundaries. These differences appeared to be attributed to the actual variation in color and composition of the respective surfaces. Talus slopes that feed into rock glaciers appeared light to medium gray in tone on the photography in response to a mixture of fine as well as blocky surface material. In contrast, rock glaciers appeared mottled because their surfaces are primarily composed of boulders and generally lack material finer than cobbles. The wave-like surfaces often visible on rock glaciers can also be used to distinguish rock glaciers from talus slopes.

Protalus ramparts develop where snow avalanches carry rock waste across snow patches. The rock waste often accumulates in ridges at the base of the snow patches. These low, irregular ridges, parallel to the cliff face, are separated from the talus by a depression formerly filled with snow (Butzer, 1976). The distinct separation from the talus wall allows protalus ramparts to be discriminated from rock glaciers. With increased rock accumulations, protalus ramparts could become rock glaciers if they grew large enough to maintain a permafrost core (Barsch, 1977).

Similar in tonal characteristics to talus slopes, avalanche chutes can clearly be distinguished from rock glaciers on aerial photographs. The chutes typically possess a steep headwall (approximately equal in slope to that of a talus slope) with a graded accumulation of rock waste consisting of cobbles to boulders at the bottom of the chute. This feature, however, shows no evidence of rock flow and can therefore be differentiated from rock glaciers on the aerial photography.

Older rock glaciers often can not be successfully distinguished from moraines utilizing aerial photographs

(Parson, 1979). Recent rock glaciers, however, can be distinguished both from older rock glaciers and moraines. The distinct tonal differences between the upper surfaces and toes of the more recent rock glaciers can be used to discriminate these features from moraines and older rock glaciers. Also, the sharp break in slope between the surface and front of the rock glaciers allow clear distinctions to be made.

Based upon the interpretation of aerial photography, 29 rock glaciers were identified on the Blanca Massif. An additional 15 rock glaciers which were identified by Parson (1979) were excluded from this study primarily because of size. Only rock glaciers with a minimum size of two hectares were investigated in this study. A map of rock glacier location on 1:24,000 U. S. G. S. 7.5 minute series quadrangles confirmed that rock glaciers did not exist in the area below 3,350 meters. The study area boundary, therefore, approximates the 3,350 meter contour around the Blanca Massif (Figure 4).

Digital Processing

All computer processing was performed at the Oklahoma State University Center for Applications of Remote Sensing (CARS). For data processing, CARS utilizes an in-house Perkin-Elmer 8/32 mini-computer and associated peripherals, including a COMTAL image-processing unit. The Earth Resources Laboratory Applications Software (ELAS) was

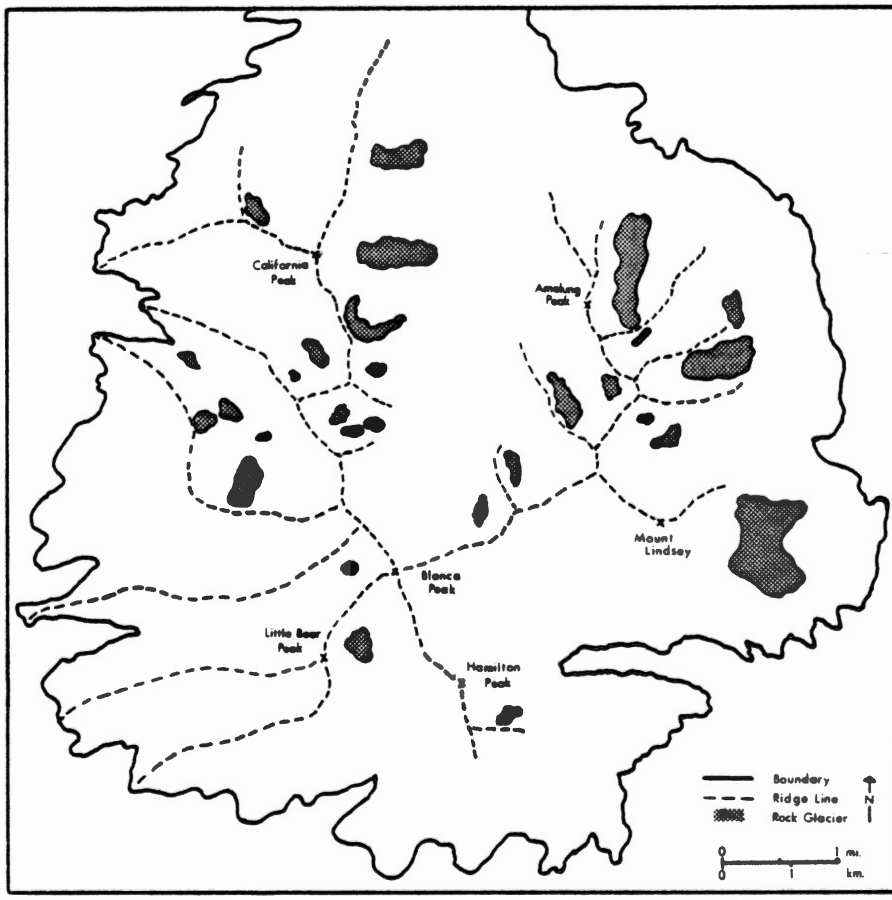

Figure 4. Distribution of Rock Glaciers in the Blanca Massif Study Area

employed for processing all digital data in this study.

Digital terrain data were used to identify the Landsat pixels above the 3,350 meter contour. The terrain data, obtained from the National Cartographic Information Center (NCIC), were recorded by the Defense Mapping Agency Topographic Center (DMATC) from the 1:250,000 scale Trinidad Quadrangle. The data, a digital representation of terrain elevations, are recorded both as contour lines and points, and stream and ridge lines. A grid of elevation values is obtained for every 2.54 millimeters on a map (approximately 50 meters ground distance). Undefined points on the grid are found by either planar or linear interpolation (U. S. G. S., 1979). The terrain data can be selectively manipulated to include, as in this case, only those data cells which are at or above 3,350 meters in the study area. Digitized elevation data can also be used to compute slope angle, slope aspect, and slope length for each data cell.

A Landsat CCT data tape, purchased from the EROS Data Center, Sioux Falls, South Dakota, provided digital data for the study area. The CCT, dated October 6, 1979, was received in the EROS Band-Interleaved-By-Line (BIL) format. An ELAS module known as NCCT reformats the EROS CCT and writes the data into a standard ELAS data file format.

Landsat data are recorded at high altitudes with a small field of view enabling the MSS data to be relatively free from panoramic distortions and relief displacements. The eastward rotation of the earth beneath the satellite during its polar-synchronous orbit causes a systematic distortion or skewing of the Landsat MSS data. This distortion can be corrected by applying algorithms to the data. Ground control points indicating features of known location must first be identified. The control points are located in terms of both their Landsat image coordinates (scan line and element) and ground coordinates (UTM coordinates as measured on a map). In the ELAS subsystem, two modules can be used for mapping Landsat data to the UTM grid (Graham and others, 1980). PMGC is used to compute mapping coefficients that relate Landsat coordinates (scan line and element) to UTM coordinates (easting and northing). This procedure corrects for skew offset, scan angle, and mirror velocity fluctuations of the scanners. Overall accuracy of the geometrically corrected image depends primarily on the accuracy of the control points. Correction errors of approximately 50 meters residual mean square (rms) have been obtained (Graham and others, 1980) and are recommended where only portions of a Landsat scene are analyzed. A 47 meter rms error was achieved in the PMGC procedure for this study area and is considered acceptable because it represents an error of less than one pixel. Another module, PMGE, resamples the Landsat data to the UTM grid using the mapping coefficients developed in the PMGC module. A nearest neighbor resampling technique was used in PMGE whereby the spectral values were resampled into a grid of 50 meter by 50 meter cells for data analysis. The resulting MSS data, with all geometric distortions removed, possessed a true north-to-south orientation and was referenced to a 1:24,000 U.S.G.S. topographic map of the area.

Analysis Techniques

Pattern recognition involves the recognition of a feature by its representative spectral characteristics. Following the reformatting and geo-referencing process, the MSS raw data were evaluated for their use in differentiating rock glaciers with pattern recognition employed as the basis for identifying spectral uniqueness. Initial evaluation of the spectral information was performed through a basic classification procedure. In this process, the computer analyzed the MSS data by simultaneously considering the information from all four Landsat data channels.

Two separate classification approaches were available for use: supervised and unsupervised (Lillesand and Keiffer, 1979). In a supervised classification, the image analyst selects the information categories or classes desired and the training areas that represent each category. The training areas, identified on the ground and on the digital data, are representative sample sites of known cover types. The classification process produces statistical classes from the digital data that are representative of each selected cover type. Every pixel is then evaluated and assigned to a class to which it is most statistically similar. If a pixel is not similar to the defined categories, then it is assigned to an undefined category. This classification approach is often used when prior knowledge and ground truth information for the study area are available and representative samples for all desired cover types can be identified.

An unsupervised classification does not utilize analyst-specified training data but examines a large number of pixels of unknown cover type and separates the pixels into classes based upon statistical similarity. The number of spectral classes produced is determined by the diversity of the MSS data and the classification criteria. The spectral values for a given homogeneous cover type should be statistically similar. Actual cover types represented by the spectral classes are identified by comparing the classified data to some form of reference data such as aerial photographs or field data. The unsupervised classification approach was used in this study to eliminate the possibility of not including representative training areas for all types of rock glaciers, thus providing sample variability.

The identification of rock glaciers was based on the application of computer manipulations and classification routines on the Landsat data and recognition of unique spectral signatures or classes representing all rock glaciers. A successful statistical grouping of reflectance values into classes, one or more of which represent only rock glaciers, would indicate an ability to use Landsat data for differentiating rock glaciers from the surrounding environment.

The initial unsupervised classification approach employed the point cluster (PTCL) search routine. PTCL collected statistics from the multi-channel Landsat data by point-by-point sampling across the data over the study area. By entering one data point at a time for the generation and merger of statistical classes, the maximum amount of discrimination between adjoining points was achieved. This procedure identified 56 statistical classes of land cover types in the study area.

The principle of maximum likelihood was employed in the classification process by utilizing the MAXL procedure. MAXL compared the variance and correlation of a data point to the statistical classes previously identified in PTCL and either included or rejected the point based upon the established statistical boundaries for each spectral class.

Computer Enhancement Techniques

A major problem encountered in this research was the adverse effects produced by sun illumination differences in mountainous environments. Computer enhancement techniques were employed in order to reduce these effects and improve the identification of rock glaciers. Several studies recommended band ratio techniques as a means for improving the overall data classification. Band ratio data are derived by dividing the spectral value in one band by the corresponding spectral value in another band for each data cell and is a suitable technique for reducing the topographic effect in multispectral data (Lyon, 1975). In this analysis, band ratios were used to reduce and/or eliminate the expression of topography (sun illumination differences) which is critical for increasing classification accuracy in a mountainous environment.

The most successful studies conducted on rock type and landform identification utilized a combination of band ratios. In studies performed by Blodget and others (1975 and 1978) and Rowan and others (1977) three sets of ratio data (band 4 to band 5, band 5 to band 6, and band 6 to band 7) were combined into a color composite image and assessed as the best combinations of band ratio data for use in rock discrimination. For this investigation, band ratio data were generated from band 4 divided by band 5, band 5 divided by band 6, and band 6 divided by band 7. A fourth channel of data was derived from the summation of the three channels of ratio data divided by three (the number of data channels summed). This fourth channel of data was used to further reduce the topographic effect in the data.

The band ratio procedure utilized the ELAS programmable calculator (PCAL) module. Necessary mathematic operations were defined before each input cell was processed, thereby creating a value for a subsequent output cell. Equation 3.1

$$R = (Bx / Bx+1) * C \quad (3.1)$$

is the mathematical expression utilized in the ratioing process where R is the digital value of the ratio process for a given cell. Bx and Bx+1 represent spectral values from two different bands of data for the same digital location. C represents a constant value necessary because the Bx/Bx+1 expression generally results in a fractional value less than the value three and ELAS rounds all fractional values to integers. Subsequently, large amounts of information would be lost without the use of such a constant. The value for C must be large enough to allow different ratio values to be represented as different integers, but small enough so that no data are lost by creating values greater than 255, the maximum data value allowed in ELAS.

A linear contrast stretch was performed on the four individual band ratio data sets. In this process, the lowest ratio value in the identified data range was assigned the value of zero while the highest ratio data value was assigned the value of 255. The remaining data values were distributed linearly between the extremes of 0 to 255. This contrast stretch technique magnified the subtle variations in brightness contained in the original data by allowing maximum separation (stretching) of the ratio values without any loss of data. All four channels of ratio data were stretched utilizing the PCAL module to a 0 to 255 range.

The linear contrast stretch algorithm used to separate the ratio values is represented by equation 3.2.

$$Yij = \frac{Xij - MIN}{MAX - MIN} * C \qquad (3.2)$$

The value Yij is the output value at location (i,j) after the contrast stretch. The variable Xij represents the input value at line i and column j. MIN and MAX represent the range of values in the particular data set being stretched, with MIN being the lowest and MAX the highest values in that data set. The constant C is a nominal value which, in this case, was 255. The value 255 was chosen to insure a 0 to 255 range for the output data set.

Finally, the four channels of stretched data were classified with an unsupervised classification approach similar to that used on the raw data. The point cluster routine (PTCL) was again used to generate statistics for use in the actual classifying procedure. A total of 49 statistical classes were identified in this procedure. The MAXL module was then used to statistically group these stretched values into individual classes.

Each of the Landsat data sets were then evaluated in terms of their success in identifying a spectral signature or set of spectral signatures that uniquely represented rock glaciers. Success was defined as a high percentage of spectral reflectance values which described only rock glaciers. Based upon recommended levels of success defined in other studies (Rowan and others, 1977, and Blodget and others, 1978), the identification of spectral signatures uniquely representative of at least 80 percent of the area of all rock glaciers would indicate an ability to discriminate rock glaciers as a unique cover type or landform on Landsat MSS digital data. Moreover, successful identification of at least 80 percent of the 29 rock glaciers in the study area would warrant rejection of the null hypothesis. The null hypothesis states that no unique spectral signature or set of spectral signatures may be identified for rock glaciers in the Blanca Massif study area. Results of this investigation will indicate the feasibility of utilizing Landsat MSS digital data in the Blanca Massif study area for the identification of rock glaciers.

Summary

The methods of analysis reviewed in this chapter were utilized to aid in rock glacier identification with Landsat MSS digital data. Aerial photographs were used to determine the boundary of the study area. The boundary was established at 3,350 meters above mean sea level or below the occurrence of rock glaciers. The four bands of Landsat data were individually analyzed and then classified with a maximum likelihood classification procedure (MAXL). Various enhancement techniques were employed to discriminate rock glaciers as a land cover type on the Blanca Massif. A band ratio procedure was utilized dividing band 4 by band 5, band 5 by band 6, and band 6 by band 7. A fourth channel of data was obtained by summing the three band ratio data sets divided by three or the number of data channels summed. All four channels of data were stretched utilizing a linear contrast stretch. The four stretch-ratio data channels were then classified using the maximum likelihood principle. The null hypothesis to be tested on the six Landsat data sets states that no unique spectral signatures may be identified for rock glaciers on the Blanca Massif. In this study, successful identification of at least 80 percent of the known rock glaciers would warrant rejection of the null hypothesis. A discussion of these results is included in the following chapter.

CHAPTER IV

RESULTS

Introduction

One of the overall goals of this study was to determine if a given reflectance value or set of reflectance values could be used to identify surfaces common to rock glaciers. To test this hypothesis, the four channels of raw Landsat data were evaluated for their usefulness in the identification of rock glaciers. Next, the four channels of raw data were classified using the maximum likelihood principle. The results were then evaluated for the ability to interpret rock glaciers from the Landsat digital data. Finally, a group of selected computer enhancement techniques were utilized on each of the four channels of raw data and classified with the maximum likelihood procedure in an effort to improve the accuracy of rock glacier identification.

The 29 rock glaciers identified and field checked during the aerial photographic interpretation were used as a basis for evaluating the analysis procedures utilized in this study. A map of the rock glaciers was transformed into digital data using an ALTEK graphic digitizer. These digital locations were used by the computer to develop geometrically referenced polygons of digital data cells. Polygons for each of the 29 rock glaciers were created using the ELAS module known as POLY. This module allows polygons to be selected by recording a series of vertices that define linear data. The constructed polygon can be stored and statistical data retrieved such as the frequency of value occurrences within a designated polygon. Information for individual class values found within a given polygon, such as frequency, percent of total frequency, and areal extent in hectares, may be generated with the PLYA module. The polygons representing the 29 rock glaciers were geometrically referenced to the Landsat data for statistical comparison of the various data sets.

Analysis of Raw Data

The four channels of raw data were evaluated to identify a unique or set of unique reflectance values to discriminate rock glaciers. A histogram illustrating the occurrence of reflectance values within the 29 rock glaciers is included for each of the four bands of data.

Count values for band 4 (channel 1) within the study area, ranged from 6 to 61. Fifteen of the 56 different count values in this range were not associated with rock glaciers, however, a majority of the count values (73 percent of the range) were found within at least one rock glacier boundary (Figure 5). The count values not present on rock glaciers represented cover types not characteristic

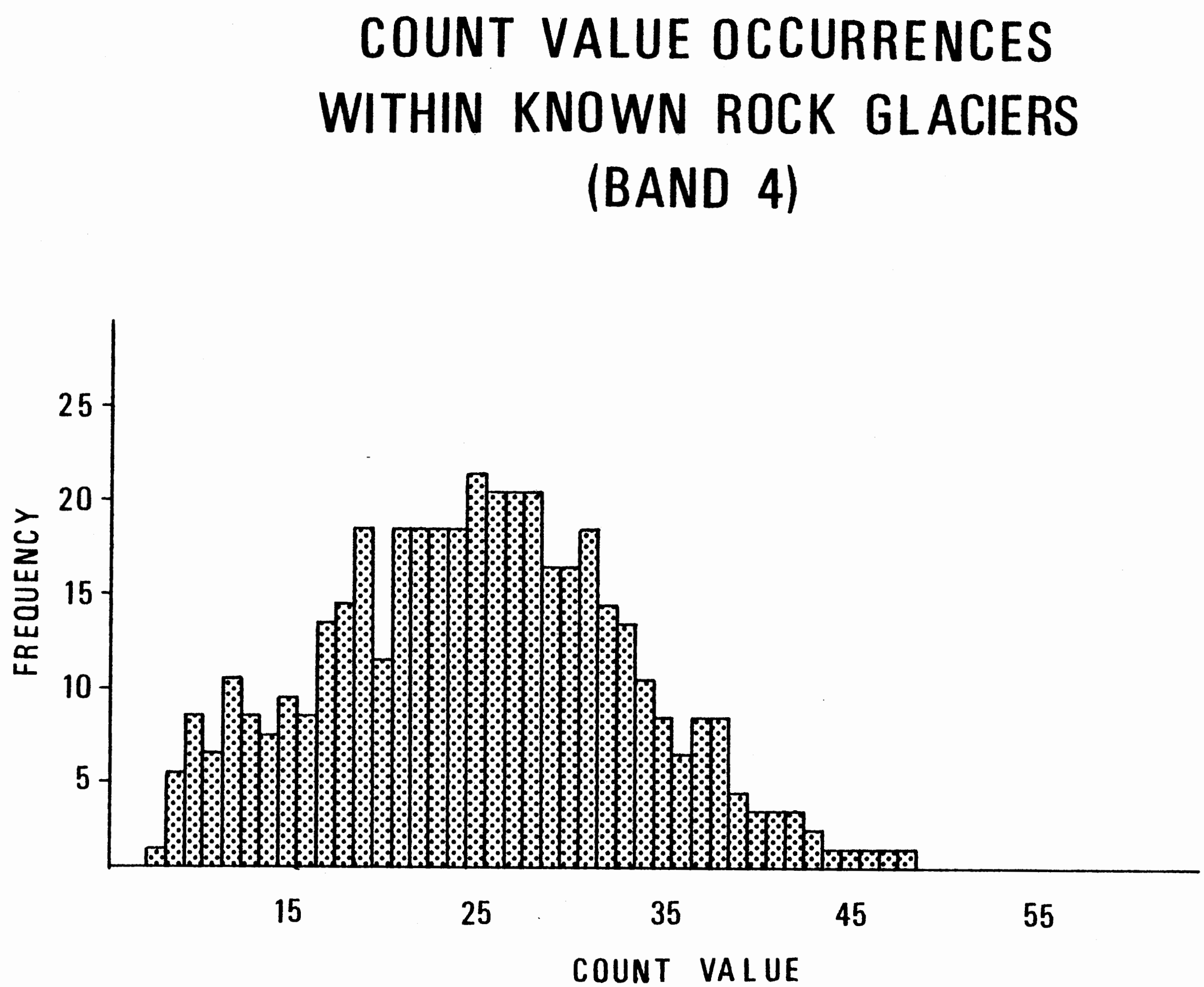

Figure 5. Count Value Occurrences Within
Known Rock Glaciers - Band 4

of rock glaciers. Twelve of the 41 count values (29 percent) associated with rock glaciers occurred in at least half of the identified rock glaciers with count value 25 present on 21 rock glaciers. The categories that best represented rock glaciers ranged from value 19 through 31 and accounted for 66 percent of the area occupied by rock glaciers. Class frequency for this range of values within rock glaciers, however, was only seven percent of the total frequency within the study area. The null hypothesis stated that no spectral signature or set of spectral signatures uniquely identifies rock glaciers. The limits of success established in this study necessitated that at least 80 percent of the total area of rock glaciers be uniquely identified by a set of spectral signatures. This range of values, values 9 through 31, could not be used alone to define rock glaciers thus resulting in the acceptance of the null hypothesis for the band 4 data set.

Count values in band 5 ranged from 6 to 84 with 54 of the count values represented in at least one of the rock glaciers (Figure 6). Of those 54 count value categories, only 11 occurred in a majority of the rock glaciers. In this instance, count values 31, 35, and 37 were the most frequently identified count values, each occurring in 19 of the 29 rock glaciers or 65 percent of the time. Actual class frequency for these values among all the rock glaciers was 16 percent. Further analyses of these three count value categories concluded that less than ten percent of their

COUNT VALUE OCCURRENCES
WITHIN KNOWN ROCK GLACIERS
(BAND 5)

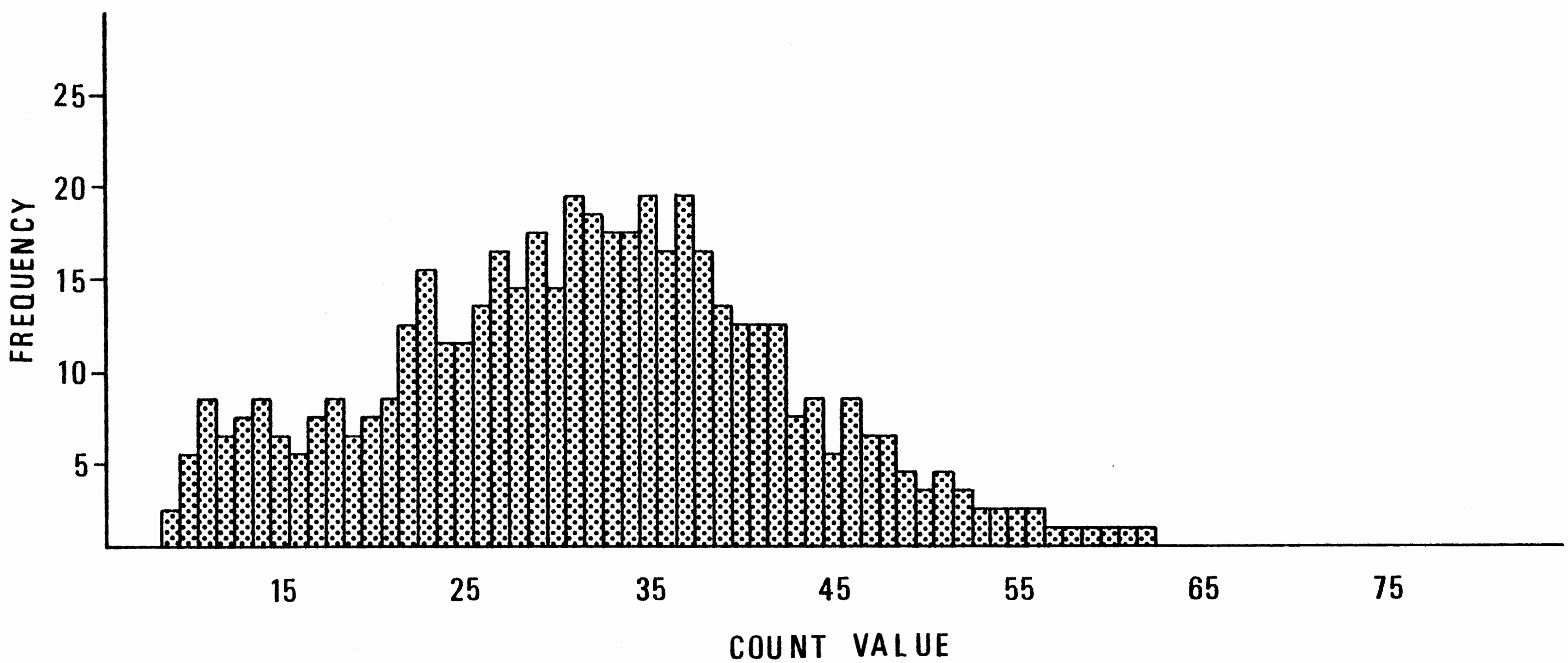

Figure 6. Count Value Occurrences Within Known Rock Glaciers - Band 5

total frequency within the study area was associated with rock glaciers. These classes, while frequently identified within rock glacier boundaries, obviously represented more than rock glaciers in this area. Data in band 5, therefore, could not be independently relied upon for identifying rock glaciers as a unique cover type on the Blanca Massif. The null hypothesis was accepted for band 5.

Count values for band 6 within known rock glaciers were located in the 7 to 62 count value range (Figure 7). The data for the entire band ranged from 4 through 79 with 55 of the 75 count values (73 percent) identified on rock glaciers. Of these 55 categories, nine count values, represented in a majority of the rock glaciers, comprised over 66 percent of the rock glacier surfaces. Only 23 percent of the frequency of occurrence throughout the study area for the nine count values, however, occurred within rock glaciers. The count values most frequently occurring within rock glaciers were not unique to rock glaciers in band 6. This band, subsequently, could not be used alone for distinguishing rock glaciers from the surrounding environment. As a result, the null hypothesis stating that no spectral signature or set of spectral signatures uniquely identifies rock glaciers was accepted.

In the same manner, band 7 was evaluated for usefulness in identifying a reflectance value or set of reflectance values which uniquely represented rock glaciers. A 0 to 65 range of count values were identified for this band of data

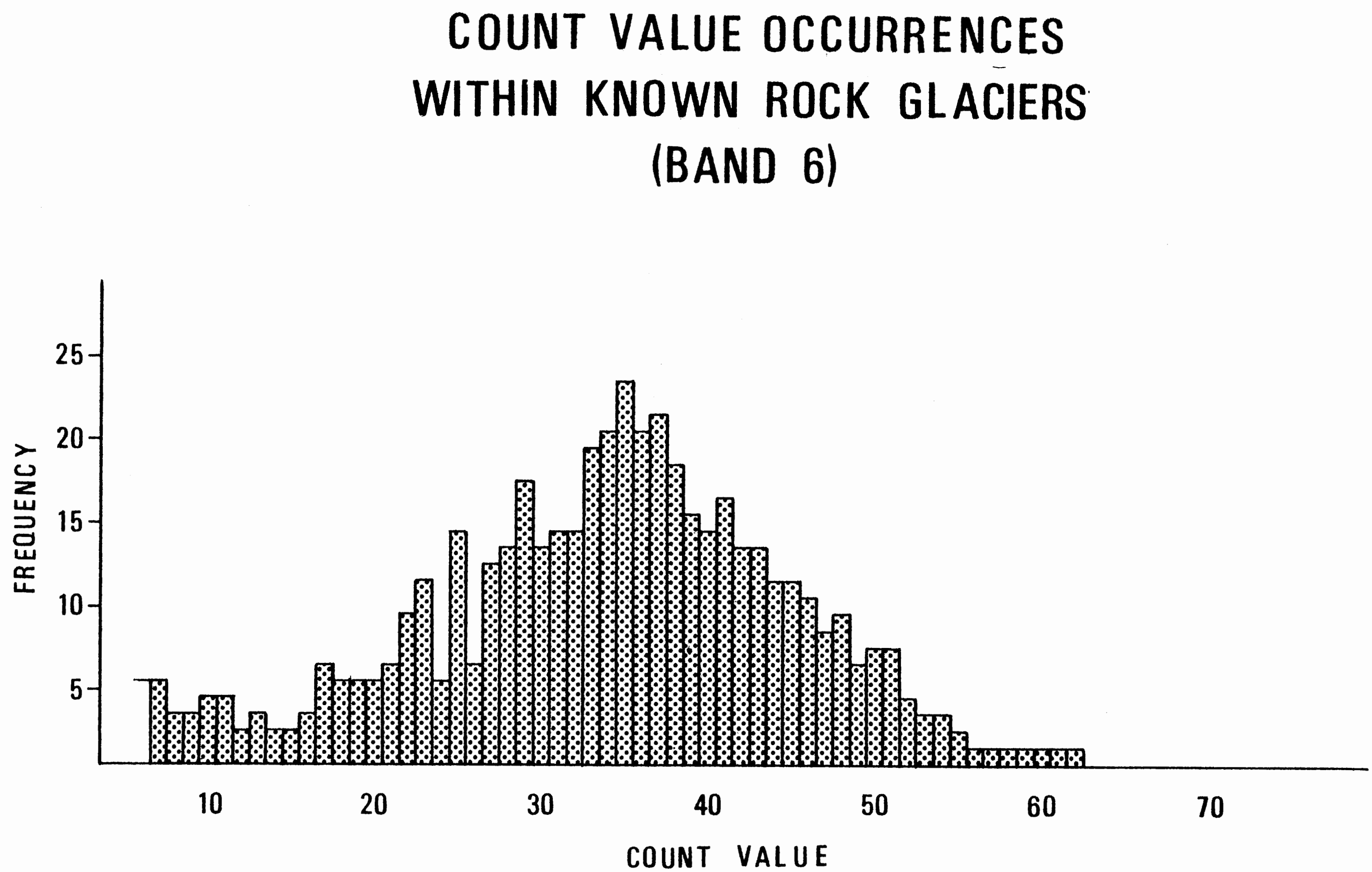

Figure 7. Count Value Occurrences Within Known Rock Glaciers - Band 6

(Figure 8). Count values on rock glaciers ranged from 2 through 49 with approximately 30 percent of these count values present in over half of the rock glacier areas. The four count values with the greatest frequency of occurrence, 26, 29, 30, and 34, accounted for only 22 percent of the data cells found in rock glaciers. These four values identified fewer than 80 percent of the area of known rock glaciers as a unique land cover type. Once again, the null hypothesis was accepted because rock glaciers could not be uniquely defined in band 7.

A spectral value or set of spectral values unique to rock glaciers could not be identified on any of the four individual bands of raw Landsat MSS data. The portions of the electromagnetic spectrum utilized in recording each of the four bands of data were inadequate in discriminating rock glaciers as a distinct land cover type in this area.

Analysis of Unenhanced Data

The individual bands of raw Landsat MSS data included reflectance values which were commonly represented on rock glacier surfaces. An analysis of a combination of these MSS bands was employed in an attempt to improve the detection of rock glaciers from the surrounding environment. The four channels of Landsat data were therefore classified with the unsupervised process previously discussed.

Class frequency counts were obtained for the 29 rock glaciers from the classified data set. Figure 9 illustrates

COUNT VALUE OCCURRENCES WITHIN KNOWN ROCK GLACIERS (BAND 7)

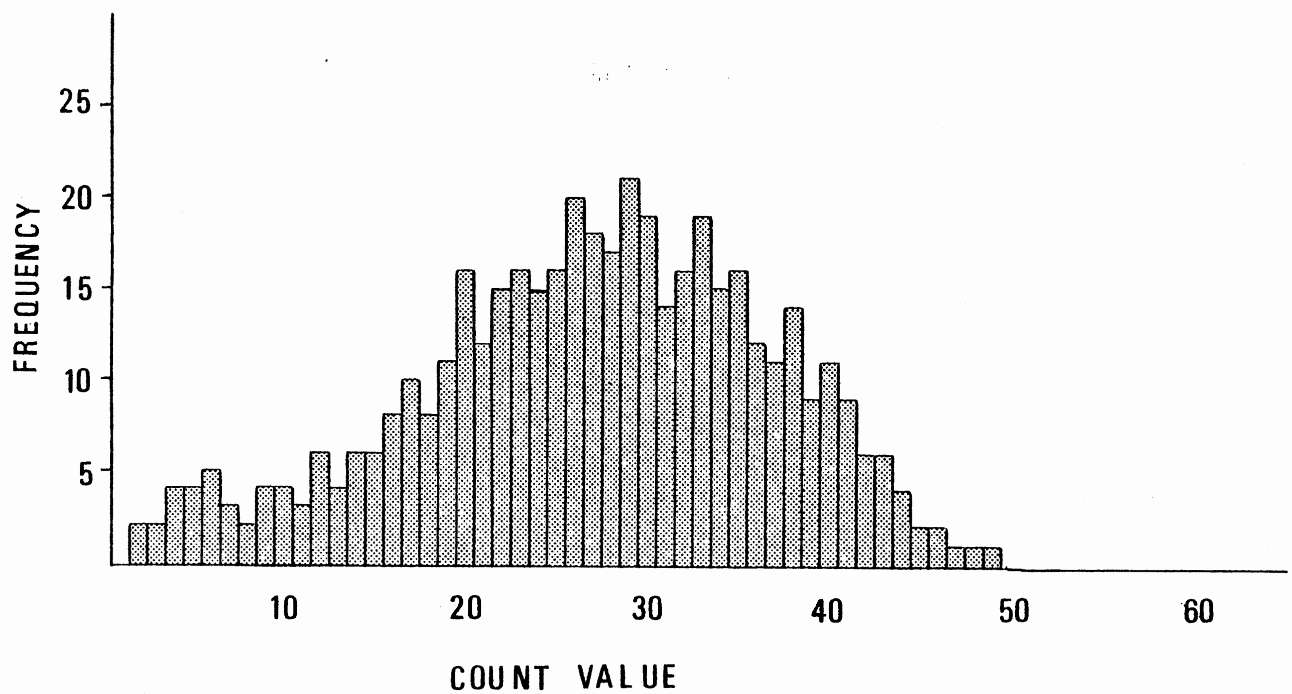

Figure 8. Count Value Occurrences Within Known Rock Glaciers - Band 7

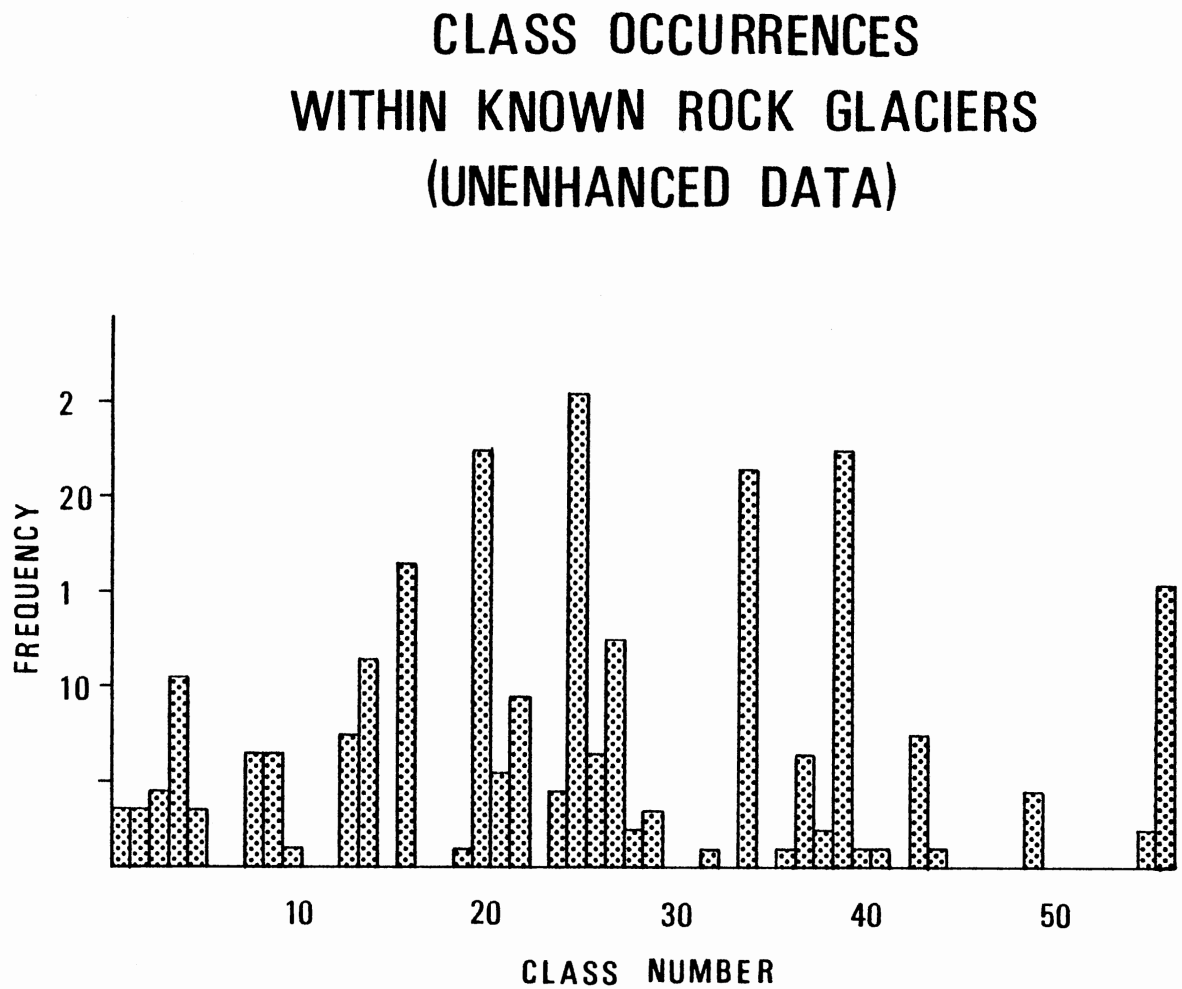

Figure 9. Class Occurrences Within Known Rock Glaciers - Unenhanced Classified Data

the frequency of class occurrences among the rock glaciers. Thirty-four of the 56 classes (61 percent) distinguished in the data set were represented within the rock glaciers, with six of the 34 classes occurring in a majority of the rock glaciers. The six major classes associated with rock glaciers (classes 16, 20, 25, 34, 39, and 56) comprised 69 percent of the total area identified as rock glaciers (Table I), rendering these classes more representative of rock glaciers than the combination of the other 28 classes.

Upon closer investigation, the six classes which predominated on rock glaciers also represented land cover types other than rock glaciers. Classes 20, 25, and 39, the largest classes represented on rock glaciers, occurred where barren rock was the predominant cover type throughout the study area. Class 34 was representative of barren rock found within shadows. Classes 16 and 56 represented rock classes with some vegetative cover also present. The remaining 28 classes represented variations of the rock cover types. These variations appeared to be a function of slope angle, slope aspect, and sun illumination. The six classes most frequently representative of rock glaciers accounted for over 68 percent of rock glacier surfaces. Over 92 percent of the area described by these classes, however, occurred outside of rock glacier areas. Overall, the unenhanced classified data failed to adequately identify classes representative of only rock glaciers in the Blanca Massif study area. In this instance, the null hypothesis

TABLE I

FREQUENCY OF CLASS OCCURRENCES - UNENHANCED CLASSIFIED DATA

CLASS NUMBER	FREQUENCY WITHIN ROCK GLACIERS	PERCENT OF ROCK GLACIER AREA	FREQUENCY OUTSIDE ROCK GLACIERS	PERCENT OUTSIDE ROCK GLACIERS
16	48	2.7	1,866	97.5
20	437	24.2	2,783	86.4
25	404	22.3	2,406	85.6
34	91	5.0	4,285	97.9
39	197	10.9	2,385	92.4
56	64	3.5	1,385	95.6
Total (6)	1,234	68.6	15,117	92.5
Other 50	567	31.4	34,237	98.4

which states that no spectral signature or set of spectral signatures can be identified that uniquely represent rock glaciers was accepted.

Analysis of Enhanced Classified Data

Failure to identify rock glaciers with unenhanced classified data led to the question, can computer enhancement techniques improve the results? Band ratio and linear contrast stretch procedures detailed in Chapter III were used prior to the classification process. Following employment of these procedures, the four derived data channels were classified using the maximum likelihood principle. Forty-nine classes were identified in this routine with 42 of the classes (86 percent) represented within known rock glaciers (Figure 10). Of the 42 classes found on rock glaciers, only six classes represented a majority of the rock glacier areas, four of which (class numbers 6, 29, 40, and 41) occurred on 20 or more rock glacier surfaces. A class frequency of 80 percent for these four classes within rock glacier boundaries implied that these classes were representative of rock glaciers (Table II).

An image of the four classes (Figure 11) illustrates the general distribution of these classes throughout the study area. The classified image was developed on the COMTAL image processing system and photographed from the screen. The identified rock glacier boundaries are shown as

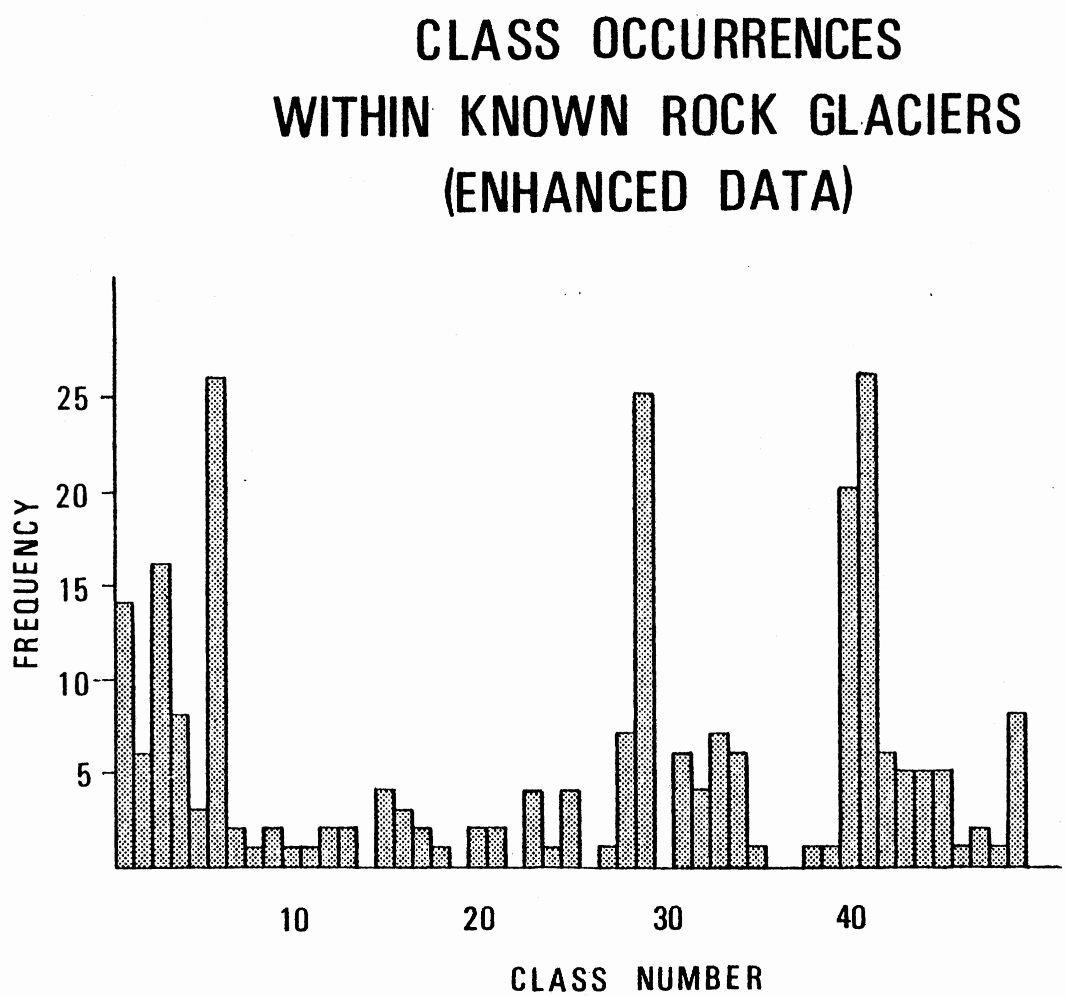

Figure 10. Class Occurrences Within Known Rock Glaciers - Enhanced Classified Data

TABLE II

FREQUENCY OF CLASS OCCURRENCES - ENHANCED CLASSIFIED DATA

CLASS NUMBER	FREQUENCY WITHIN ROCK GLACIERS	PERCENT OF ROCK GLACIER AREA	FREQUENCY OUTSIDE ROCK GLACIERS	PERCENT OUTSIDE ROCK GLACIERS
1	95	5.2	3,778	97.5
3	48	2.6	2,075	97.7
6	464	26.8	4,981	91.5
29	513	28.3	8,164	94.1
40	66	3.7	1,455	95.7
41	378	20.9	4,084	91.5
Total (6)	1,564	86.9	26,222	94.3
Other 43	237	13.1	23,369	99.0

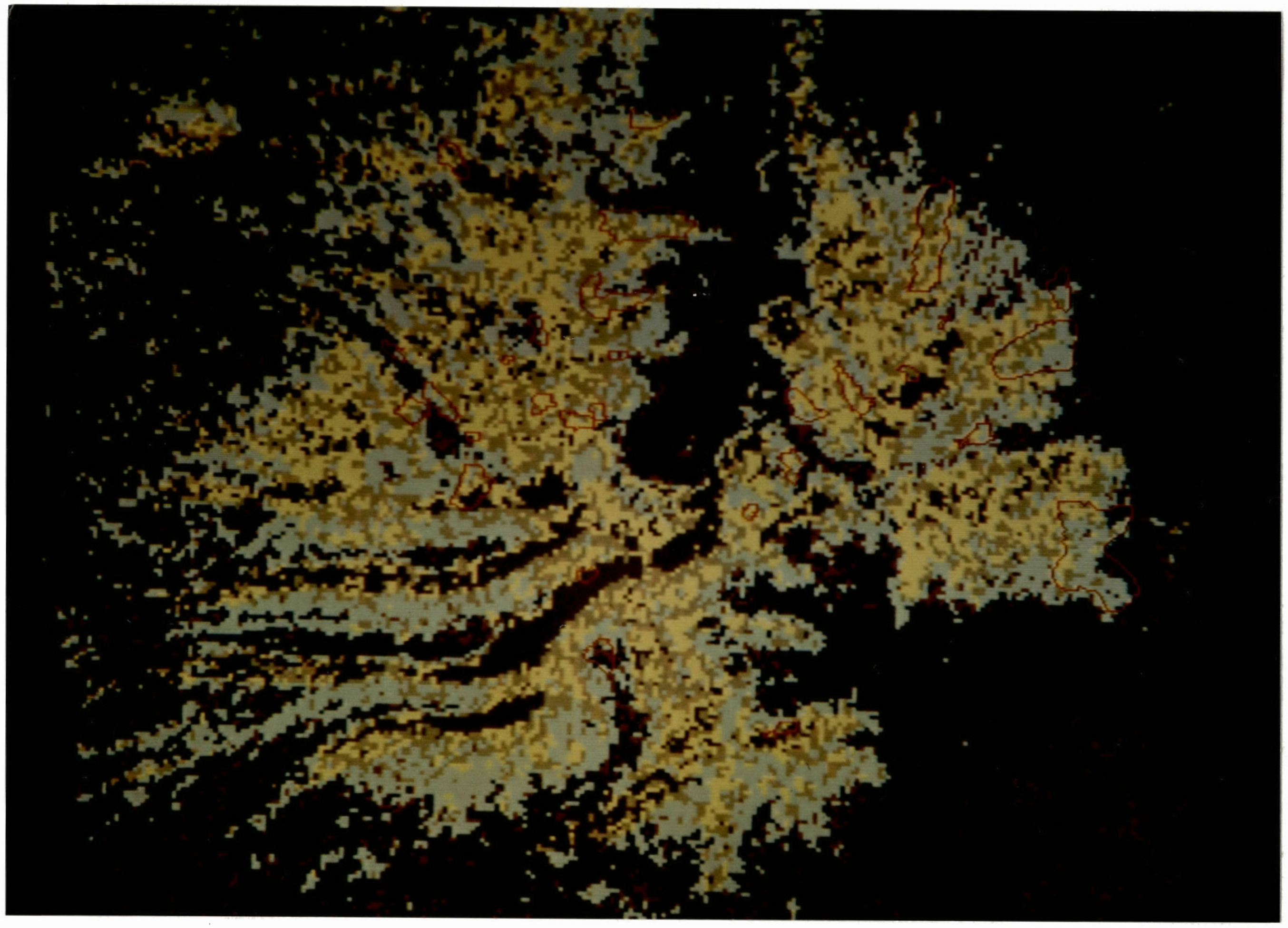

Figure 11. Image of Study Area - Enhanced Classified Data

red polygons. Class 6 (yellow) and class 41 (gold) represent barren rock cover types. Class 29 (pale green) represents a barren rock cover type which is highly reflective and commonly found on east-southeast-facing slopes and/or gently sloping terrain. A rock cover type with some vegetation is represented by class 40 (blue). This class primarily depicts exposed rock with a light herbaceous plant cover. The other classes found on rock glaciers (brown) are more predominantly representative of vegetative cover types or shadowed areas. The distribution of those classes which were unrelated to rock glaciers are represented in black. These classes were commonly located in valleys and/or on northwest facing slopes where sun-illumination was minimal. They represent areas with reduced reflectance values indicative of vegetated and/or shadowed areas.

Overall, the examination of reflectance characteristics on rock glaciers within the study area did not discriminate classes uniquely representative of rock glaciers. The six major classes which represented rock glaciers covered over 86 percent of all rock glacier surfaces. Over 94 percent of these six classes common to rock glaciers, however, occurred outside the identified rock glacier areas. Less than six percent of the area occupied by the six major classes occurred within rock glacier boundaries. These six classes, therefore, did not identify rock glaciers as a unique cover type. As a result, the null hypothesis was accepted.

Comparison of Classified Data Sets

A major goal of this research was to identify a procedure or set of procedures to be used with Landsat MSS digital data that would most clearly distinguish rock glaciers from the surrounding environment. A comparison of the two classification procedures was conducted to determine if enhancement techniques improved rock glacier interpretation from the data. Class frequency counts for the 29 rock glaciers were analyzed from the classified data sets to determine the best procedure for rock glacier identification. Thirty-four of the 56 classes distinguished in the unenhanced data set were represented in the rock glaciers. In the enhanced data, 42 of the 49 classes occurred within rock glaciers. The enhanced data set contained a broader range of classes associated with rock glaciers (86 percent) than the unenhanced data set (61 percent). The unenhanced data set, therefore, identified fewer classes associated with rock glaciers.

The actual frequency of class occurrence within rock glacier boundaries indicated the uniqueness of the classes for rock glacier identification. In the unenhanced data set, six classes were identified that were represented in a majority of the 29 rock glaciers. Four of the classes (class numbers 20, 25, 34, and 39) had a combined frequency of occurrence of 62 percent among the rock glaciers delineating a majority of the rock glacier surfaces. In the enhanced data set, four classes (class numbers 6, 29, 40, and 41) were represented on a majority of the rock glacier surfaces. The four classes had an 80 percent combined frequency of occurrence indicating an 80 percent chance that these classes were represented within a given rock glacier. The statistics indicate that the enhanced data set aided in the discrimination of a set of four classes which were more uniquely representative of rock glaciers than the four classes which best defined rock glaciers in the unenhanced data set and represented rock glaciers only 62 percent of the time (Tables II and I, respectively). Based on these results, the enhancement techniques used on the Landsat MSS data in this study allowed more accurate identification of classes representative of known rock glaciers than the unenhanced classified data.

Neither analysis procedure identified unique spectral values or classes representative of only rock glaciers. The six major classes found on rock glaciers identified in the unenhanced and enhanced data sets had a high frequency of occurrence outside the rock glaciers (92 and 94 percent, respectively). The classes primarily identified exposed rock throughout the study area. The enhanced data set, however, more clearly contained a set of classes representative of rock glacier surfaces than the unenhanced data set. The six classes common to rock glaciers in the enhanced data set accounted for 87 percent of all rock glacier surfaces, while the six major classes identified in the unenhanced data set identified only 62 percent of the rock glacier surfaces. The techniques utilized to enhance the Landsat MSS data, therefore, improved Landsat's capability for identifying rock glaciers.

Summary

The goal of this study was to assess the feasibility of utilizing Landsat MSS digital data and specific computer algorithms to identify rock glaciers. Various analysis techniques utilized on the Landsat MSS digital data were evaluated for an ability to detect similar surface characteristics on rock glaciers. The objective, to identify a reflectance value or set of reflectance values representative of a rock glacier cover type or landform, was not satisfactorily accomplished.

Bands 4, 5, 6, and 7 were individually assessed for a capability to discriminate rock glaciers from the surrounding environment. None of these individual bands provided reflectance values which uniquely described rock glaciers. These bands were then classified and subsequently re-evaluated for a capability to discriminate rock glaciers from the surrounding environment. The unenhanced classified data yielded several classes which occurred in most of the rock glaciers. A high percentage of these classes, however, were also found throughout the rest of the study area. Rock glaciers, therefore, could not be discriminated on the unenhanced data as a unique cover type.

The raw data were enhanced using band ratio and linear

contrast stretch routines to aid in data analysis. Six classes were identified on the enhanced data which appeared to be unique to rock glaciers. Approximately 87 percent of all rock glacier surfaces were represented by these six classes. These classes were not, however, unique to rock glaciers, but rather were found throughout the study area. Overall, the classes found on rock glaciers identified in the enhanced data set were more representative of rock glaciers than the other Landsat data sets.

The unenhanced and enhanced classified data sets identified a set of reflectance values which discriminated rock glaciers to a varying extent. None of the Landsat MSS data sets or analysis techniques examined in this research, however, identified a reflectance value or set of reflectance values unique to rock glaciers. The null hypothesis tested in this study stated that no unique spectral signature or set of spectral signatures on Landsat MSS digital data could be identified for rock glaciers in the Blanca Massif study area. This hypothesis was accepted for all six Landsat data sets analyzed in this research. Results, therefore, indicated that the utilization of Landsat MSS digital data and the specific computer enhancement techniques employed in this study provided an insufficient method for accurate identification of rock glaciers. A discussion of why rock glaciers were not identified as a unique class or set of classes is presented in the concluding chapter.

CHAPTER V

CONCLUSIONS

The approach and techniques utilized in this study to identify rock glaciers on the Blanca Massif via Landsat MSS digital data are exploratory. The goal, to identify rock glaciers as a unique cover type or landform on Landsat MSS data, was not satisfactorily accomplished. One explanation is that rock glaciers cannot be identified as unique, spectral signatures in mountainous environments. The results and conclusions presented in this thesis indicate that Landsat data and selected computer enhancement techniques provide only a limited capability to identify rock glaciers, a specific geomorphic landform. The spectral signatures associated with rock glaciers did, however, identify certain surface characteristics of rock glaciers in this research. These characteristics suggest that different enhancement techniques or the inclusion of additional data sources may improve the results in other research efforts. As such, continued investigation to identify spectral signatures representative of surface landforms with Landsat MSS data appears warranted.

Capabilities of Landsat Data

Advantages of utilizing data acquired from the Landsat system on earth resources are numerous. The satellites (Landsats -1, -2, and -3) provide a synoptic view of 34,225 square kilometers per scene. As a result, many surface features can be analyzed for the price of one MSS scene of data. The multispectral view, with two channels beyond the visible region of the spectrum, increases the information obtained from selected study sites. Accessibility of data is an advantage in utilizing Landsat MSS data over conventional aerial photography or ground surveys. Landsat can provide repeat data for any area between 81 degrees North and 81 degrees South latitudes upon request. Finally, if the utilization of Landsat data is warranted, the products are relatively inexpensive when compared to the costs associated with traditional methods of land cover mapping or data collection.

The data provided on Landsat CCT's are digital values or in a quantitative form which allows statistical and other mathematical functions to be rapidly and efficiently utilized. The MSS recognizes 128 gray tones or ranges of information in Bands 4, 5, and 6 (0-127), and 63 in Band 7, many more than the human eye can possibly distinguish which may improve scene interpretations.

In this research, a set of classes were identified in the unenhanced and enhanced classified data sets that were common to most rock glaciers. Four distinct cover types were recognized: barren rock on steep to relatively steep slopes, barren rock on gentle slopes, vegetated rock surfaces, and exposed rock in shadowed areas. The classified data sets clearly identified areas comprised primarily of rock. Differentiation between predominately rock surfaces and vegetated surfaces was excellent. An ability to identify rock surfaces common to rock glaciers is essential, especially in areas where prior knowledge of surface conditions is unavailable.

The environment in which rock glaciers exist is often inaccessible making the utilization of Landsat data a practical source of data. The data provide repeat coverage for very large areas over all types of terrain. Although field investigations increase the accuracy of analyzed data, ground-truth data can not always be obtained. In this case, Landsat's greatest usefulness may be its capability to gather information from areas where little or no ground-truth data are available (Rundquist, 1978).

Limitations of Landsat Data

The Landsat system imposed limitations of: resolution, in that features smaller than a pixel (0.45 hectares) in size could not be mapped; dimension, in that no information could be recovered regarding altitude variations in surface features; and season, in that maximum exposure of rock glaciers occurred from the beginning of August to mid-October (the time of relatively snow-free conditions on the

Blanca Massif). Conditions of optimum sun illumination could not be obtained. Rock glaciers generally occur in rugged mountainous terrain which causes shadowing problems. In addition, the best season for direct illumination of rock glaciers (dates with snow-free conditions) do not coincide with the year's highest sun angle.

A variety of problems related to the nature of rock glaciers and to the classification of these surface features also limited the successful application of Landsat MSS data. Problems attributable to variations in sun illumination must be considered. Steep slopes in mountainous areas reflected in-coming solar radiation differently causing ambiguities in surface reflectance for similar cover types. As confirmed in a study by Rundquist (1978), moraines, barren rock, and scree on talus slopes had nearly identical reflectance signatures and often could not be accurately identified. The same problem was encountered in this research.

Another problem was related to the resolution of the Landsat digital data. Since the value assigned to a pixel represents an average reflectance value for a 79 meter by 57 meter area, edges of features or boundaries between cover types were not always distinct. The arbitrary arrangement of the grid of pixels on the earth's surface as well as the averaging of reflectance values over the pixel area contributed to this problem. In this analysis, the edges of rock glaciers, defined by the contact lines between the talus slopes and the head of the rock glacier and by the toe at the terminus of the rock glacier, could not be clearly defined. These edges often appeared as transitional zones so that the exact location of the border of rock glaciers was ambiguous on each of the Landsat data sets. Border pixels reduced the overall accuracy in identifying rock glaciers as a distinct landform. Moreover, the accuracy was severely reduced for small, irregularly shaped rock glaciers which were quite common in this study area. On these rock glaciers, border pixels comprised a significant number of pixels out of the total number of pixels defined as the rock glacier.

The effects of shadows posed another major problem in the analysis, especially with the individual bands of raw MSS data. The band ratio and contrast stretch techniques reduced the sun illumination effects over most rock glacier areas. The techniques aided in smoothing out the differences in the extreme reflectance values from the sun illuminated and shadowed sides of the mountains, but did not eliminate them from affecting the results of the analysis.

Variations in rock composition among the different rock glaciers also posed problems in the data analysis. Rock glaciers originating from different rock sources possess slightly different reflectance characteristics, which resulted in a number of classes being associated with rock glaciers during the analysis. The variability in rock type throughout the area was at least partially responsible for the wide range of classes associated with rock glaciers.

In summary, the basic reasons why rock glaciers were not interpreted from the Landsat MSS data as a unique cover type can be attributed to the environment in which they are found. Variations in rock reflectance resulting from sun illumination effects, shadow problems, orientation of the rock glaciers, composition, size, and similar reflectance from barren rock throughout the study area were all factors which limited the successful identification of rock glaciers with Landsat MSS digital data.

Recommendations

Rock glaciers could not be differentiated from the surrounding environment using the techniques specified in this study. To improve the application of digital mapping of rock glaciers and other alpine landforms, further testing and procedural refinements with Landsat data are warranted. Landform classifications can perhaps be improved through additional research on band ratio and contrast stretch manipulations, supervised classification procedures, and discriminant analysis of the features associated with rock glaciers. The incorporation of other enhancement and classification techniques, not yet examined, might improve Landsat's capability for identifying rock glaciers as a unique cover type.

Ancillary data, such as large-scale digital terrain data, may be incorporated to improve the overall classification results. Digital terrain data, at a scale of

1:250,000, were utilized in a previous classification procedure (Gregory, 1982) providing slope angle information. This information was acquired to aid in the definition of rock glacier boundaries and areas with slope angles characteristic of rock glacier surfaces (mean slope of 9.6 degrees). Topographic data at this scale did not distinguish between rock glacier surfaces and associated talus slopes (mean slopes of 37.2 degrees) because of the linear interpolation factors inherent in the generation of the contoured data. Use of Digital Elevation Models (DEM's), at a scale of 1:24,000, could provide the data necessary to improve classification results. These data would more accurately identify low slope angle classes over the smaller rock glacier surfaces present in mountainous environments.

Establishment of a minimum size of rock glaciers for identification is recommended. The resolution of Landsat limits the possible size range of rock glaciers that can be discriminated. In this study, rock glaciers smaller than two hectares were eliminated from the investigation. Accurate discrimination of rock glaciers smaller than two hectares is currently impossible. Surface characteristics common to rock glaciers must be identifiable on the Landsat data for accurate discrimination.

The effects of border pixels which represent a transitional area at the edges of the rock glaciers must also be considered. In this research, spectral values associated with abrupt changes in slope angle at the edges of the rock glaciers were not clearly identified. Overall accuracy in rock glacier discrimination was significantly reduced because of failure to identify rock glacier boundaries. Border pixels, representative of neither rock glacier surfaces nor surrounding talus slopes or vegetative cover, were responsible for the failure to discriminate the edges of rock glaciers. These pixels, often the predominate pixels of small rock glaciers, prohibited accurate discrimination of the smaller rock glaciers. Elimination of problem border pixels in the data is essential for precise identification of rock glaciers. Utilization of DEM data will aid in eliminating interpretation problems associated with border pixels.

Future capabilities of remote sensing could provide the necessary data for accurate and efficient identification of rock glaciers. A multispectral scanner known as the Thematic Mapper (TM) will have a resolution of 30 meters by 30 meters, compared to the 79 meter by 57 meter resolution of the present satellite. The TM is scheduled for operation with the launch of Landsat-4 in July, 1982. The data could conceivably improve the results of the present research. In addition to better resolution, the TM will increase the number of spectral bands to seven and change the band width and location on the electromagnetic spectrum. This increased information could provide the source of Landsat data necessary to discriminate individual landforms, specifically rock glaciers, from the surrounding environment.

Presently, identification of a reflectance value or set of reflectance values which uniquely discriminate rock glaciers on Landsat MSS digital data on the Blanca Massif cannot be obtained. Surface characteristics unique to rock glaciers could not be accurately interpreted from any of the Landsat data sets analyzed in this research. Quite possibly, rock glaciers cannot be identified by unique, spectral signatures.

A procedure to analyze the pattern or arrangement of spectral signatures characteristic of rock glaciers may provide a more accurate method of identifying rock glaciers on Landsat MSS data. Spectral signatures should represent the contact line present between the talus slope and the rock glacier; the toe of the rock glacier; and the ridges and furrows commonly found on rock glacier surfaces. Future recognition of a pattern of spectral signatures unique to rock glaciers may be enhanced through the utilization of digital terrain data (providing large-scale elevation and slope angle information) and Thematic Mapper data (with increased spatial resolution and spectral discrimination capabilities) analyzed with additional computer enhancement techniques. Improved data could increase Landsat's capability for discriminating rock glaciers and other geomorphic phenomena, thus warranting further research.

SELECTED BIBLIOGRAPHY

American Geological Institute, 1976, Dictionary of Geological Terms: New York, Anchor Press/Doubleday, Second Edition, 472 p.

Barsch, D., 1977, Nature and Importance of Mass-wasting by Rock Glaciers in Alpine Permafrost Environments: Earth Surface Processes, vol. 2, p. 231-245.

Blodget, H. W., Brown, G. F., and Moik, J. G., 1975, Geological Mapping in Northwestern Saudi Arabia Using Landsat Multispectral Techniques: NASA Earth Resources Surv. Symp., vol. 1-B, p. 971-989.

Blodget, H. W., Gunther, F. J., and Podwysocki, M. H., 1978, Discrimination of Rock Classes and Alteration Products in Southwestern Saudi Arabia With Computer-Enhanced Landsat Data: NASA-TP-1327, 40 p.

Butzer,Karl W., 1976, Geomorphology From the Earth: New York, Harper and Row, 463 p.

Cole, M. M., and Edmiston, C. J., 1980, HCMM and Landsat Imagery for Geological Mapping in Northwest Queensland: London, London Univ. Geog. Dept., University Press, 7 p.

Goetz, Alexander F. H., and Rowan, Lawrence C., 1981, Geologic Remote Sensing: Science, vol. 211, p. 781-791.

Graham, M. H., Pearson, R. W., Seyfarth B. R., Junkin, B. G., and Kalic, M. T., 1980, ELAS: Earth Resources Laboratory Applications Software; National Space Technology Laboratories, NASA, Bay St. Louis, Mississippi, 463 p.

Gregory, Mark S., 1982, The Reduction of Shadowing Effects in the Classification of Landsat Digital Data: Program Abstracts, Assoc. of Amer. Geog., San Antonio, Texas, p. 113.

Hoffer, Roger M., ed., 1974, An Interdisciplinary Analysis of Colorado Rocky Mountain Environments Using ADP Techniques: Purdue Univ., Laboratory for Applications of Remote Sensing, Research Bull. 919, 124 p.

Houston, Robert S., Marrs, Ronald W., and Smithson, Scott B., 1976, Type III - Final Report on Application of Landsat Images to Geologic Mapping in the Ice-free Valleys of Antarctica: NASA, Goddard Space Flight Center, Greenbelt, Maryland, NASA-CR-147237, 73 p.

Hunt, Graham R., and Salisbury, John W., 1978, Assessment of Landsat Filters for Rock Type Discrimination, Based on Intrinsic Information in Laboratory Spectra: Geophysics, vol 43, no. 4, p. 738-747.

Johnson, J. P., 1973, Some Problems in the Study of Rock Glaciers: Research in Polar and Alpine Geomorphology, 3rd Guelph Symp. of Geomorphology, Geog. Pub. no. 3, Dept. of Geog., Univ. of Guelph, p. 84-94.

Lillesand, Thomas M., and Kieffer, Ralph W., 1979, Remote Sensing and Image Interpretation: New York, John Wiley and Sons, 612 p.

Lintz, Joseph, and Simonett, David S., 1976, Remote Sensing of Environment: Reading, Addison-Wesley Pub. Co., 694 p.

Lyon R. J. P., 1975, Mineral Exploration Applications of Digitally Processed Landsat Imagery: Proc., First Annual William T. Pecora Memorial Symp., Souix Falls, South Dakota, p. 271-292.

Nyberg, Rolf, 1980, Mapping of Landforms From Stereoscopic Landsat Imagery - A Case Study From the Scandinavian Mountains: Geografiska Annaler, vol. 62, Ser. A 3-4. p. 219-227.

Osborn, Gerald D., 1975, Advancing Rock Glaciers in the Lake Louise Area, Banff National Park, Alberta: Canadian Jour. Earth Sci., vol. 12, p. 1060-1062.

Outcalt, S. I., and Benedict, J. B., 1965, Photo Interpretation of Two Types of Rock Glaciers in the Colorado Front Range, U.S.A.: Jour. of Glac., vol. 5, p. 849-856.

Parson, Charles G., 1979, Rock Glaciers and Site Characteristics on the Blanca Massif in South-Central Colorado: Iowa City, Univ. of Iowa, Dept. of Geog., Ph.D. Dissertation, 212 p.

Podwysocki, Melvin H., Gunther, Fred J., and Blodget, Herbert W., 1977, Discrimination of Rock and Soil Types by Digital Analysis of Landsat Data: NASA-TM-71290, 44 p.

Potter, N. Jr., 1972, Ice-cored Rock Glacier, Galena Creek, Northern Absaroka Mountains, Wyoming: Geol. Soc. of Am. Bull., vol. 83, p. 3025-3058.

Raines, Gary L., and Lee, Keenan, 1974, An Evaluation of Multiband Photography for Rock Discrimination: Colorado School of Mines, Remote Sensing Rept. 74-4, 36 p.

Rowan, Lawrence C., Goetz, Alexander F. H., and Ashley, Roger P., 1977, Discrimination of Hydrothermally Altered and Unaltered Rocks In Visible and Near Infrared Multispectral Images: Geophysics, vol. 42, no. 3, p. 522-535.

Rundquist, Donald C., ed., 1978, The Use of Landsat Digital Information for Assessing Glacier Inventory Parameters: An Evaluation: Omaha, Univ. of Nebraska at Omaha, Dept. of Geog./Geol., 148 p.

Sabins, Floyd F. Jr., 1978, Remote Sensing: Principles and Interpretation: San Francisco, W. H. Freeman and Co., 426 p.

Salisbury, John W., and Hunt, Graham R., 1974, Remote Sensing of Rock Type in the Visible and Near-Infrared: Proc. Ninth Intern. Symp. on Remote Sensing of Environment, p. 1953-1958.

Schneider, Stanley R., McGinnis, David F. Jr., and Pritchard, John A., 1979, Use of Satellite Infrared Data for Geomorphology Studies: Remote Sensing of Environment, vol. 8, p. 313-330.

Shroder, John, 1981, Personal Communication, Univ. of Nebraska at Omaha, Dept. of Geog., Omaha, Nebraska, November, 1981.

Siegal, Barry S., and Gillespie, Alan R., 1980, Remote Sensing in Geology: New York, John Wiley and Sons, 702 p.

Slater, Phillip N., 1980, Remote Sensing: Optics and Optical Systems: Reading, Addison and Wesley Pub. Co., 575 p.

Swain, Phillip H., and Davis, Shirley M., eds., 1978, Remote Sensing: The Quantitative Approach: New York, McGraw-Hill, 396 p.

Thompson, W. F., 1962, Preliminary Notes on the Nature and Distribution of Rock Glaciers Relative to True Glaciers and Other Effects of the Climate on the Ground in North America: Int. Assoc. Sci., Hydrol., Pub. 58, Symp. Obergurgl., p. 212-219.

U. S. Geol. Surv., 1979, Digital Terrain Tapes, Users Guide, Second Edition: Dept. of the Interior, Washington, D. C., Government Printing Office, 12 p.

Verstappen, H. Th., 1977, Remote Sensing in Geomorphology: Amsterdam, Elsevier Scientific Pub. Co., 212 p.

Wahrhaftig, C., and Cox, A., 1959, Rock Glaciers in the Alaska Range: Geol. Soc. of Am. Bull., vol. 70, p. 383-436.

White, P. Gary, 1979, Rock Glacier Morphometry, San Juan Mountains, Colorado: Geol. Soc. Am. Bull., Pt. II, vol. 90, no. 6, p. 924-952.

White, S. E., 1975, Additional Data on Arapaho Rock Glaciers in Colorado Front Range, U.S.A.: Jour. of Glac., vol. 14, no. 72, p. 529-530.

_______, 1976, Rock Glaciers and Block Fields, Review and New Data: Quaternary Research, vol. 6, p. 77-97.

APPENDIX

AERIAL PHOTOGRAPHY KEY FOR ROCK GLACIERS

Topography

<u>Uneven</u>

Surfaces appear wave-like with many ridges and furrows. The surfaces are comprised primarily of boulders and generally lack material finer than cobbles. Talus slopes found at the head and toe of the landforms appear smooth in texture.

Drainage

<u>Internal</u>

The blocky, hummocky surfaces have very high percolation rates and very rapid internal drainage for the first three to five meters which does not allow sufficient runoff for the creation of an integrated drainage.

Tone

<u>Mottled</u>

The finely textured rock fragments at the head and toe of rock glaciers appear light to medium gray. The rock glacier surfaces appear mottled because of highly varied textures across the surfaces of the landforms.

Vegetation and Land Use

Barren and Natural

The lack of soil development and the rugged topography do not present favorable conditions for the establishment of land uses. Talus slopes above and below the rock glaciers often possess a discontinuous light cover of sedges and other herbaceous plants. Older rock glaciers may possess similar vegetation cover with tree growth possible.

Gullies

None

Because of the high permeability of the feature, sufficient runoff to create gullying does not occur.

VITA 2

Susan Mary Berta

Candidate for the Degree of

Master of Science

Thesis: THE ANALYSIS AND INTERPRETATION OF SPECTRAL REFLECTANCE SIGNATURES FROM ROCK GLACIERS

Major Field: Geography

Biographical:

Personal Data: Born in Flint, Michigan, July 29, 1957, the daughter of Julius and Mary Berta.

Education: Graduated from Holy Rosary High School, Flint, Michigan, in June, 1975; received Bachelor of Arts degree in Geography from The University of Michigan - Flint, in May, 1979; completed requirements for the Master of Science degree at Oklahoma State University in July, 1982.

Professional Experience: Graduate Research Assistant, Center for Applications of Remote Sensing, Department of Geography, Oklahoma State University, May, 1980 - July, 1982.

Professional Organizations: Member, Association of American Geographers; student director, AAG Remote Sensing Specialty Group; member, American Society of Photogrammetry; Vice-president, Gamma Theta Upsilon.