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GEOLOGIC AND MINERAL AND WATER RESOURCES INVESTIGATIONS IN WESTERN COLORADO USING ERTS-1 DATA: PROGRESS REPORT IX

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16. Abstract Topography was found to be the most important factor defining folds on ERTS imagery of northwestern Colorado; tonal variations caused by rock reflectance and vegetation type and density are the next most important factors. Photo-linears mapped on ERTS imagery of central Colorado correlate well with ground-measured joint and fracture trends. In addition, photo-linears have been successfully used to determine the location and distribution of metallic mineral deposits in the Colorado Mineral Belt. "True" color composites are best for general geologic analysis and false color composites prepared with positive/negative masks are useful for enhancing local geologic phenomena. During geologic analysis of any given area, ERTS imagery from several different dates should be studied.

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PREFACE

On 30 June 1972 a contract was awarded to the Colorado School of Mines for research in the interpretation of ERTS-1 imagery and supporting aircraft data and their application to mineral and water resources investigations. This work is being done by five faculty members and two graduate student research assistants in the Department of Geology and by research scientists in the Planetary Geology Laboratory at Martin-Marietta Corporation/Denver Division. The objectives of this investigation are:

1) the extraction of basic geologic information from ERTS imagery,
2) the application of this basic geologic information to the study of mineral resources, volcanic phenomena, and water resources in central and western Colorado, and
3) input to the study of the effects of the atmosphere on ERTS MSS imagery.

ERTS imagery of central and western Colorado contains an extraordinary amount of basic geologic information. Much of this information can be extracted straight from the four bands of MSS imagery using standard photogeologic interpretation techniques. Color additive viewing methods that produce a nearly true color rendition of the ERTS scene increase the general geologic interpretability of the imagery. False color renditions prepared by color additive viewing of positive/negative masks appear to be helpful in enhancing some geologic phenomena, particularly photo-linears.

Basic geologic information extracted from ERTS imagery of central Colorado has been used to study the location and distribution of metallic mineralization in the Colorado Mineral Belt. Photo-linears mapped on the ERTS imagery are particularly useful in selecting potential target areas for exploration.

Seasonal variations in solar elevation and azimuth angle, snow cover, vegetation growth vigor, and surface water runoff tend to enhance different geologic phenomena at different times of year. Therefore, routine geologic analysis of a given area should use ERTS imagery acquired at several times of year.

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INTRODUCTION

This report summarizes the work conducted by the Colorado School of Mines during the period 1 June - 30 November, 1973, under contract NAS5-21778 to the National Aeronautics and Space Administration/Goddard Space Flight Center. During the reporting period the basic geologic information content of ERTS-1 imagery of central and western Colorado was further evaluated. Several imagery enhancement and interpretation techniques were tested for their utility in revealing additional basic geologic information.

Photo-lineament data from ERTS-1 imagery of central Colorado were applied to the study of the location and distribution of metallic mineral deposits in the Colorado Mineral Belt, and a study of the use of basic geologic information from ERTS-1 imagery for petroleum exploration was initiated.

Additional solar radiation and rock reflectance measurements were made during ERTS passes in order to acquire the data necessary for studying the affects of the atmosphere on ERTS/MSS data. Ground geologic investigations were conducted during June, July, and August both for the purpose of checking prior ERTS imagery interpretations and for obtaining the information required to make subsequent image interpretations more meaningful.

BASIC GEOLOGIC INFORMATION

The Colorado School of Mines has been concerned with analyzing and evaluating ERTS-1 imagery for the purpose of discriminating and identifying geological phenomena in central and western Colorado. For the past year, five faculty members and two research assistants in the Department of Geology at the Colorado School of Mines have been engaged in various lines of investigation utilizing ERTS-1 imagery. The extraction of basic geologic information is fundamental to this investigation, since the type and amount of geologic information that can be extracted from ERTS images will bear directly on the potential usefulness of the imagery for application to specific geologic problems. Basic geologic information consists of the knowledge of the location and distribution of rocks and soils, geologic structures, and landforms. This knowledge is <u>basic</u> to all geologic investigations, be they mineral exploration programs, dam sitings, highway routings, groundwater studies, or whatever.

Research at the Colorado School of Mines has been pointed towards determining (1) how much and what kind of basic geologic information can be extracted from ERTS imagery, and (2) what physical characteristics or parameters at the surface are the most important in allowing basic geologic information to be obtained from the ERTS imagery. The approach generally has been to look at ERTS imagery over areas with which individual researchers were geologically familiar to see if specific lithologic contacts, structures, and landforms could be detected, and to document the surface characteristics that make detection possible using personal knowledge of the features, published geologic maps and descriptions, field checks, and especially, high and low-altitude aircraft photography.

FOLDS

Lithologic contacts, geologic structures, and geomorphic features as detected on ERTS imagery are closely related phenomena. This fact is well-illustrated in a study of folds in an oil-producing area in northwestern Colorado (Fig. 1). The area includes portions of the Piceance basin, Uinta Mountains, White River Plateau, and Green River basin; the Green River oil shales are exposed in the south-central portion of the image.

Positive transparencies of the four MSS bands (1:1,000,000) were studied stereoscopically and also pseudo-stereoscopically using bands 5 and 7 of the same image as a stereo pair. The troughlines and crestlines of 63 folds were identified and plotted on a clear acetate overlay (Fig. 2).

The question was then asked, "What physical parameters at the surface made it possible to identify the folds on the ERTS imagery?". To get at the answer the imagery was

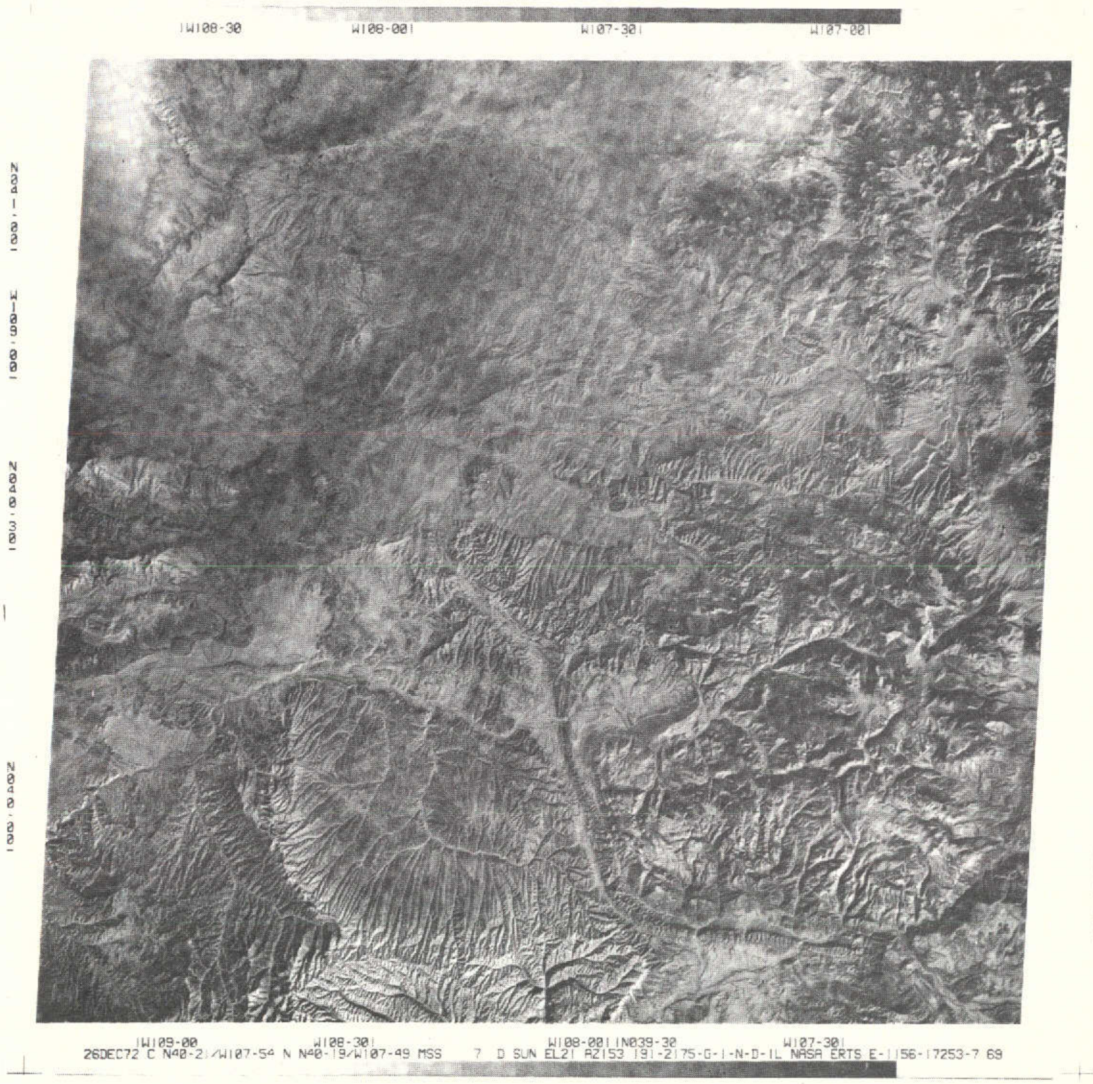

Fig. 1. ERTS-1 image 1156-17253-7 of northwestern Colorado. Photo-interpretation of the 4 MSS bands of this scene revealed the 63 folds shown in Figure 2.

Figure 2. Troughlines and crestlines of 63 folds identified on ERTS-1 image 1156-17253 (Fig. 1).

re-examined and the folds were classified according to size and detectability (Table 1) and physical characteristics (Table 2). Only four surface manifestations of the folds were found to be important in identifying the fold structures on the ERTS imagery:

1. Tonal pattern - includes apparent lithologic banding caused both by differences in rock and soil spectral reflectance and by differences in vegetation type and density, primarily the latter.
2. Broad-scale topographic expression.
3. Opposing dip slopes - a small-scale form of topographic expression.
4. Stream patterns.

Most of the mapped folds are relatively small (56) and obscure (32) on the imagery (Table 1). As can be seen from Table 2, some folds will be obvious on ERTS imagery if they are expressed by lithologic banding or topography, however, it is very clear that in order to extract the maximum amount of fold information from the imagery it is necessary to interpret small-scale, subtle geomorphic features such as stream patterns and dip slopes. Furthermore, it is apparent that geomorphic expression is the most important factor in identifying folds on the ERTS imagery.

Since the image originally used for the fold interpretation was acquired during mid-winter, it was thought that

		DETECTABILITY		
	Obvious	Evident	Obscure	TOTAL
SIZE: **LARGE** Major folds that can be traced for tens of kilometers	3	1	3	7
SIZE: **SMALL** Minor or secondary folds mostly on flanks of LARGE folds.	12	15	29	56
TOTAL	15	16	32	63

Table 1. Size and detectability of the 63 folds mapped on ERTS image 1156-17253.

PHYSICAL CHARACTERISTICS DEFINING FOLDS

DETECTABILITY	Tonal Pattern	Topographic Expression	Dip Slopes	Stream Patterns
Obvious	9	15	0	1
Evident	3	14	5	2
Obscure	0	0	32	4
TOTAL	12	29	37	7

Table 2. Number of folds identified on ERTS-1 image 1156-17253 classified according to detectability and the surface characteristics that defined them. Note that a number of folds were manifest by more than one surface characteristic and, hence, the total number of folds is greater than 63.

perhaps topographic enhancement caused by the low solar inclination angle combined with partial snow cover may have caused the geomorphic (topographic) factors to appear more important in fold mapping than might be the general case. Therefore, a snow-free, high sun-angle image of the same scene was interpreted. The results were that fewer folds could be detected and that those folds that were found were less well-expressed. It was concluded that geomorphic features are, in fact, the most important factors in the detection of folds on the ERTS imagery of northwestern Colorado and that images acquired during mid-winter provide the best data.

PHOTO-LINEARS

Probably the most obvious geologic features that are found on ERTS imagery are the photo-linears. In central and western Colorado, photo-linears are abundant, are easily extracted from ERTS imagery, and appear to provide significant information about the structural and tectonic framework. Consequently, studies have been conducted on methods of analyzing this photo-linear information and in determining the capability of mapping faults on ERTS imagery.

Trend Analysis: Trend analyses have been run on photo-linear data from two ERTS scenes of central Colorado (Figs. 3 and 4). Image 1172-17141 is cloud-free, but heavily

Figure 3. ERTS image of central Colorado used in photo-linear trend analysis. Cloud-free and heavily snow-covered.

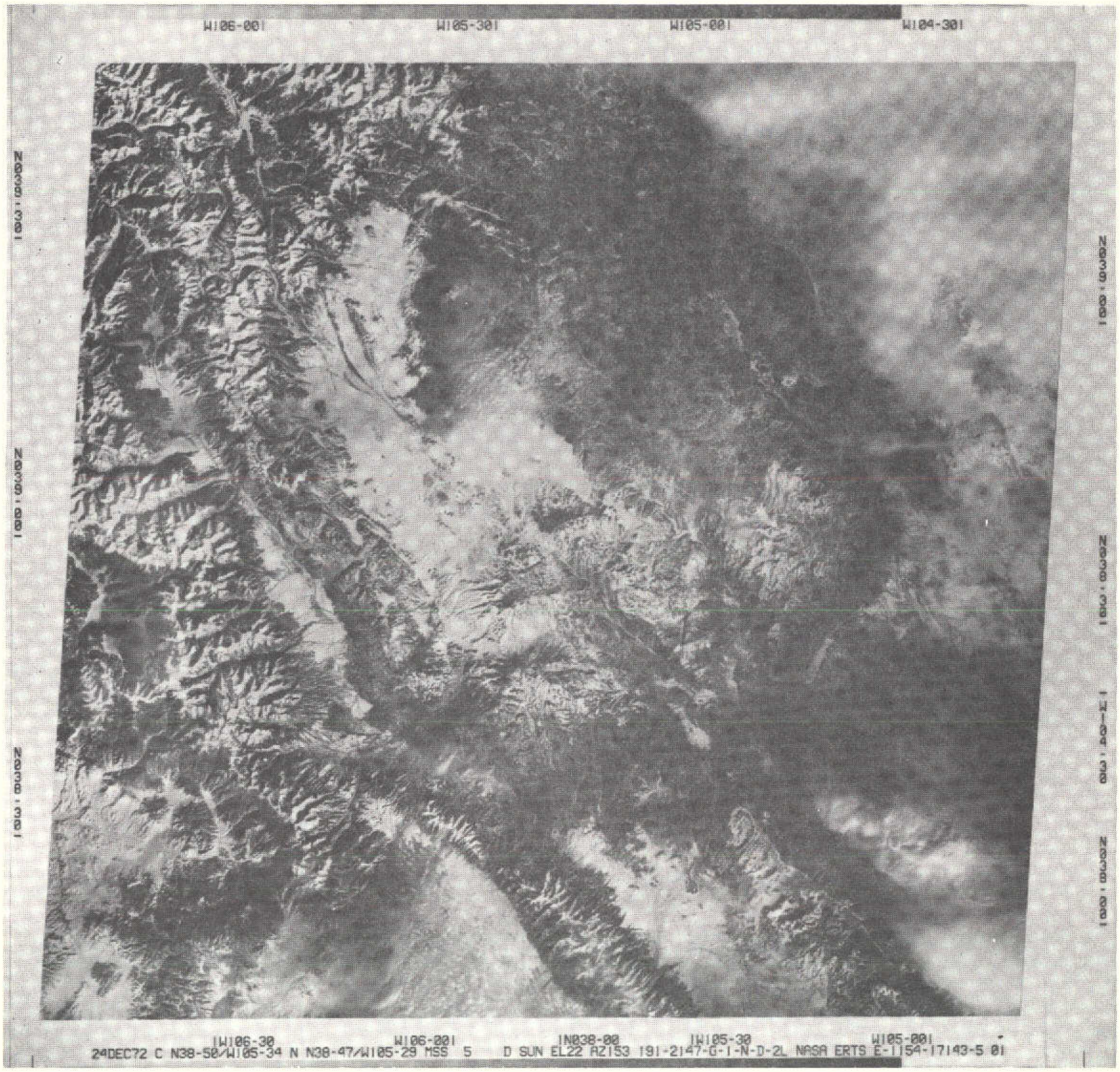

Figure 4. ERTS image of central Colorado used in photo-linear trend analysis. Snow-free and 30% cloud covered.

snow-covered; image 1154-17143 is snow-free, but has about 30% cloud-cover.

The photo-linear analysis was performed in several steps. First, the photo-linears are mapped on an overlay. The mapped photo-linears are then hand coded according to azimuth, length, and location, and this information is punched onto computer cards and submitted to the computer. The computer program used produces a strike frequency graph, a smoothed strike frequency graph, and a table of significance values of the frequencies on the graphs. Maxima in the smoothed strike frequency graphs that have significance values greater than 90 are believed to represent significant linear trends.

Analysis of the photo-linear data from the two sets of ERTS images of the central Colorado scene showed that the significant trends are identical, except for one trend (Fig. 5). Analysis of both sets of photo-linear data together revealed eight significant trends.

In addition to the ERTS photo-linears, studies were made of 1) the photo-linears identified on a plastic relief map of the same general area, illuminated from four directions at a low illumination angle, and 2) the data from two of the ground fracture sets, the South Park and Phantom Canyon sets (Fig. 5).

Interestingly, four of the ERTS trends were also found in the data from the plastic relief map. The trends from

Linear and Fracture Trends

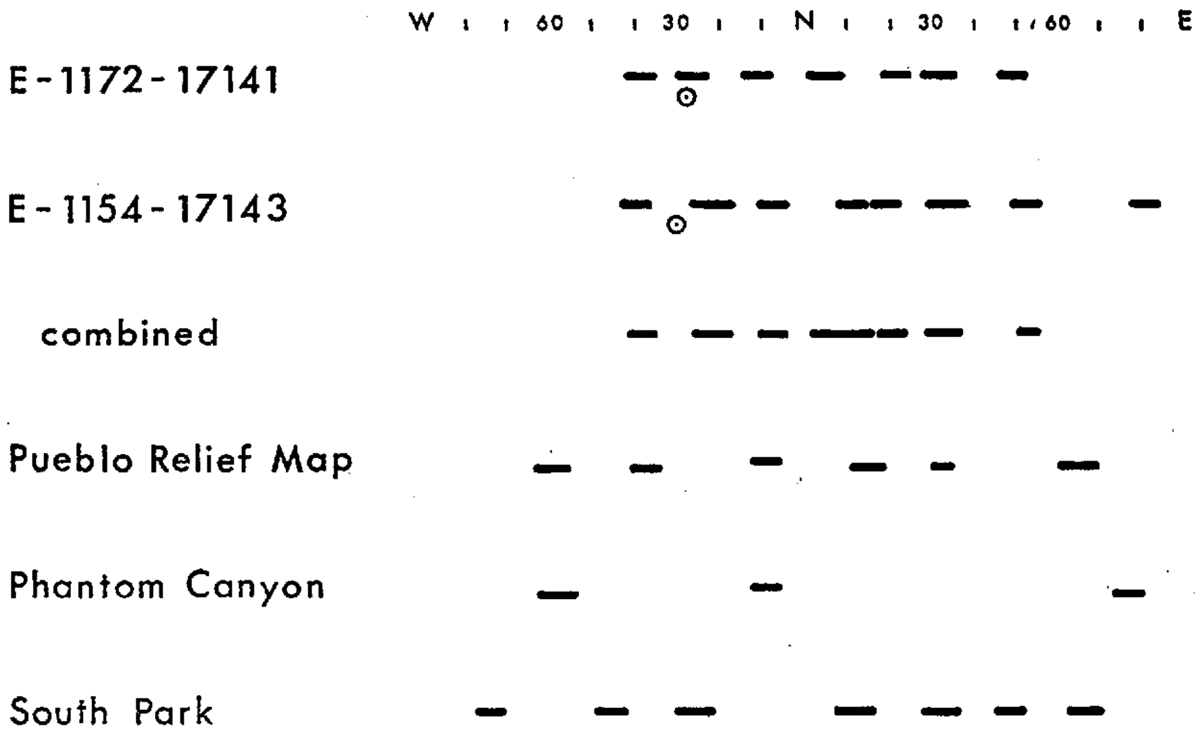

Figure 5. Results of trend analyses conducted on ERTS photo-linears, plastic relief maps, and ground fracture measurements in central Colorado.

the ground data correlate well with the ERTS trends, however, several trends are significant in these local areas, but not in the area of the ERTS imagery as a whole. Note that the significant trends in the two ground data sets are mutually exclusive.

The results of the trend analyses are still being geologically interpreted, so definitive geological explanations are forthcoming. It does appear that ERTS linear trends correspond well with known regional joint set trends; some local joint set trends, however, do not show up as significant ERTS linear trends.

Fault Mapping: Some 650 linear miles of photo-lineaments were mapped in the Colorado mineral belt between Climax on the north and Taylor Reservoir on the south. Approximately two-thirds of these lineaments could be correlated with known faults. The faults thus mapped represent about ten percent of the total faulting present in the area as reported by previous workers, but include most of the major faults such as the Mosquito-Weston fault system and the London Fault system. The lineaments mapped provide a good general outline of the regional fault pattern present in the area.

INTERPRETATION TECHNIQUES

During the studies of the basic geologic information content of ERTS images, various interpretation techniques have been employed. Efforts at the Colorado School of Mines have generally been restricted to interpretation techniques that could be used by the practicing geologist who has a minimum of training in remote sensing. The rationale for this is that the primary geologic user of ERTS imagery, that is, the practicing geologist affiliated with industry, a governmental agency, or a university, does not ordinarily have the budget or the sophisticated laboratory facilities necessary to persue high-powered data processing and enhancement techniques. Therefore, efforts at the Colorado School of Mines have been concentrated toward the following:

1. Stereoscopic and monoscopic photo-interpretation of 10- by 10-inch positive transparencies and prints, enlarged to as much as 1:250,000.
2. Color additive viewing using the four MSS bands.
3. Color additive viewing using various positive/ negative masks.

Even with these relatively simple and inexpensive interpretation techniques, the amount of basic geologic information that can be extracted from the ERTS imagery of central and western Colorado has far exceeded initial expectations.

ERTS Imagery: The researchers at the Colorado School of Mines who have been studying the ERTS imagery of central and western Colorado all agree that color additive viewing increases the capability to extract basic geologic information, except on snow-covered scenes. All color additive viewing at the Colorado School of Mines has been done with an I^2S viewer. Although many color renditions have been looked at, the most useful has been found to be a "true-color" rendition formed by projecting band 4 with green, band 5 with red, and band 6 with additional green in order to further bring up vegetation. One drawback to this particular color rendition is that water bodies are not easily seen. One way to rectify this situation, without destroying the "true-color" rendition of the rest of the scene, is to add a negative of one of the infrared bands to the optical system and project it with blue light with the result that water bodies can be plainly identified, and the rest of the scene is essentially unchanged. Some caution must be used in interpreting such a color rendition since cloud and terrain shadows also will appear blue. However, shadows generally appear much darker blue in relation to water bodies. This is one example of the utility of positive-negative color additive viewing, others are currently being investigated.

The results of the fold study in northwestern Colorado suggest that spectral contrast (color) of lithologic units is not of prime importance in determining the structure of the area from ERTS imagery. However, spectral contrast is found to be important in central Colorado. Detectable spectral contrast also offers some hope of identifying areas of mineralization and alteration (color anomalies) from ERTS imagery where the areal extent of such areas is one-half mile or greater. Furthermore, this spectral contrast is best brought out by color additive viewing.

In summary, the results of investigations to date indicate that the optimum data format for routine geologic interpretation in central and western Colorado consists of stereo pairs of prints or transparencies, as near to "true-color" as possible, enlarged to a scale of 1:1,000,000 or larger. The scale used is largely determined by the size and number of the features to be annotated on the imagery.

Supporting Aircraft Photography: The use of Kodak color compensating (CC) filters for photogeologic interpretation was suggested by NASA personnel during fall, 1972. By way of investigating the use of these filters, two sets of metal clips were designed to fit over the stereo lenses of a Bausch & Lomb Zoom 240 stereoscope. These clips hold from one to three CC filters mounted in 35mm slide frames and allow rapid and easy removal and replacement of the filters. A variety of Kodak CC filters was purchased and tried on supporting color and color infrared aircraft photography.

In general, it was found that CC filters having number designations of less than 20 (CC10M, CC5R, etc.) were of little or no value in photointerpretation. Those filters having number designations of 20 or greater (CC20M, CC50R, etc.) were found to be of value in photointerpretation either when used alone or when used in combination. In general, the CC filters were found to be useful for the following purposes:

1. Adjusting or changing the color balance of the photography without expensive reprocessing.
2. Yellow CC filters (absorb blue) were found to be useful for enhancing areas of hydrothermal alteration or iron stain in color photography.
3. Cyan CC filters (absorb red) were found to useful for enhancing lineaments above timberline in color photography.
4. Good results were obtained by using combinations of green, yellow, and cyan CC filters with color photography to first enhance the affects of vegetation, then, turning around and using combinations of red, blue, and magenta CC filters to subdue the affects of vegetation. A similar procedure was followed with CIR photography, also with good results.

5. Similarly, other combinations of CC filters can be used to enhance or subdue any other affects that can be attributed to colors, such as rock or soil color.
6. There seems to be a beneficial "psychological enahncement" produced when, after looking at a stereo pair of photographs for some period of time, any CC filter is inserted. The photography then appears to be somehow new and different, and additional information can be seen. This affect exists, whether or not any real enhancement of these features occurs, as once a feature is detected in this manner, it can often be seen equally-well with or without the presence of the CC filter.

The CC filters were used in routine photogeologic interpretation of stereo pairs of color and color infrared transparencies (they would have no value for use with black and white photography). The results obtained would probably apply equally well to color and color infrared prints. A similar method could, no doubt, be devised to use CC filters with a mirror stereoscope or even a small pocket stereoscope. The filters, mounts, clips, etc., are cheap and easily purchased or made, hence, this technique is a simple and inexpensive method of extracting additional information from available color and color infrared photography.

MINERAL EXPLORATION WITH ERTS IMAGERY

Mineral exploration is an often-cited potential application of orbital remote sensing data. However, before a new method, system or instrument is employed by industry, it must show potential use and economic feasibility. In this light, an experiment was designed to test the application of photo-lineament information obtained from ERTS imagery to the selection of potential target areas for mineral exploration. The objectives of the experiment were:

1) To select potential target areas based on the distribution of photo-lineaments and their intersections, as obtained from the ERTS image.
2) To evaluate the target areas.
3) To determine what relationships, if any, exist between the distribution of photo-lineament intersections and the location of mineral districts.

The test area was defined by a single ERTS image of central Colorado (Fig. 6), which includes a part of the Colorado Mineral Belt, and thus, several major mining districts. The northeast-trending mineral belt is characterized by intrusive porphyries of Late Cretaceous and early Tertiary age (1). Ore deposition, in most cases, was structurally controlled by faults and shear zones.

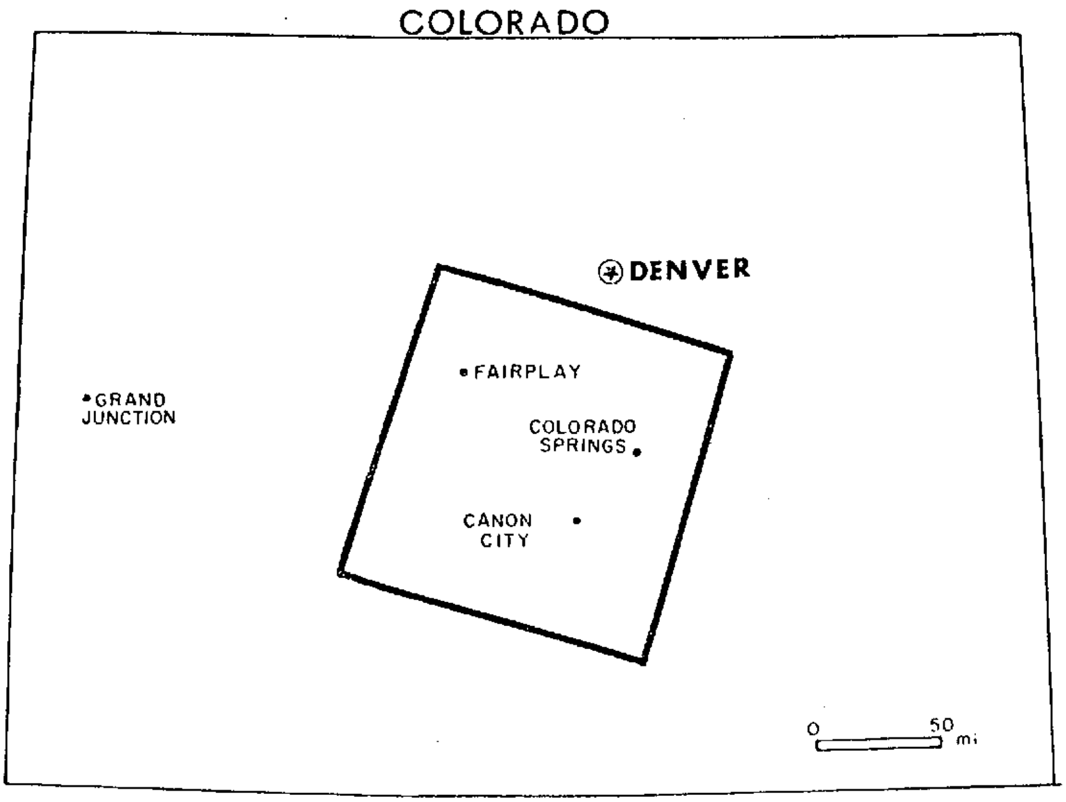

Figure 6 . Colorado index map. Geographic location of the ERTS imagery used in this investigation.

PHOTOINTERPRETATION

Photointerpretation was performed on the 11 January 1973 image 1172-17141 (Fig. 7) using a Bausch & Lomb zoom stereoscope in both stereoscopic and monoscopic modes. The 9.5 x 9.5-inch positive transparencies of all four MSS bands were used; however, most of the data was obtained from band 7. This image was chosen over other images of the same scene because the topography is enhanced by the low-angle solar illumination (23^{0} elevation) and snow cover in the mid-winter imagery. The first step of the experiment consisted of interpreting the ERTS image and plotting the photo-lineaments on an overlay (Fig. 8). Two types of elements were plotted: straight lineaments and curvilinear, or circular, features.

TARGET AREA SELECTION

Potential reconnaissance target areas were selected on the basis of the lineament data obtained. Selections were made under the following assumptions:

1) We are looking for metallic mineral deposits
2) Mineralization is probably structurally related to faults and shear zones, which may, in turn, be spatially related to intrusive stocks, plugs and volcanic centers.

Target selection consisted of two steps. First, about 40 small, specific targets were chosen based on the numbers and kinds of photo-lineament intersections. Next, the 10

Figure 7. 11 January 1973 ERTS image 1172-17141-7.

Figure 8. Photo-lineament overlay. Solid lines are well-defined linears; dashed lines are possible or moderately expressed linears; dotted lines are curvilinear or circular features.

best target areas (Fig. 9) were selected from the first group. Each target area corresponds to a circular area on the ground about 14 km (9 mi) in diameter or approximately 165 sq km (64 sq mi). The 10 final target areas were broken down into three orders of priority (1, highest, etc.) based on the complexity, type and strength of the intersections and the presence or absence of curvilinear or circular features. Of these criteria, complex areas of intersections and intersections of photo-lineaments with curvilinear or circular features were felt to be the most important.

TARGET AREA EVALUATION

A map of Colorado mineral deposits (2) was used to evaluate the target areas. The location of the larger mineral districts and the selected target areas are shown in the overlay in Figure 10. Most of the annotated mineral districts have produced over $100,000 in metals; however the combined production of Climax, Leadville and Cripple Creek has been over $1,000,000,000 in precious and base metals. Other important mineral districts which have had production figures over $1,000,000 include Breckenridge, Kokomo, Alma, and Bonanza. Five of the 10 target areas coincide with the following mineral districts: Breckenridge, the Leadville-Climax-Alma area (covered by one target area),

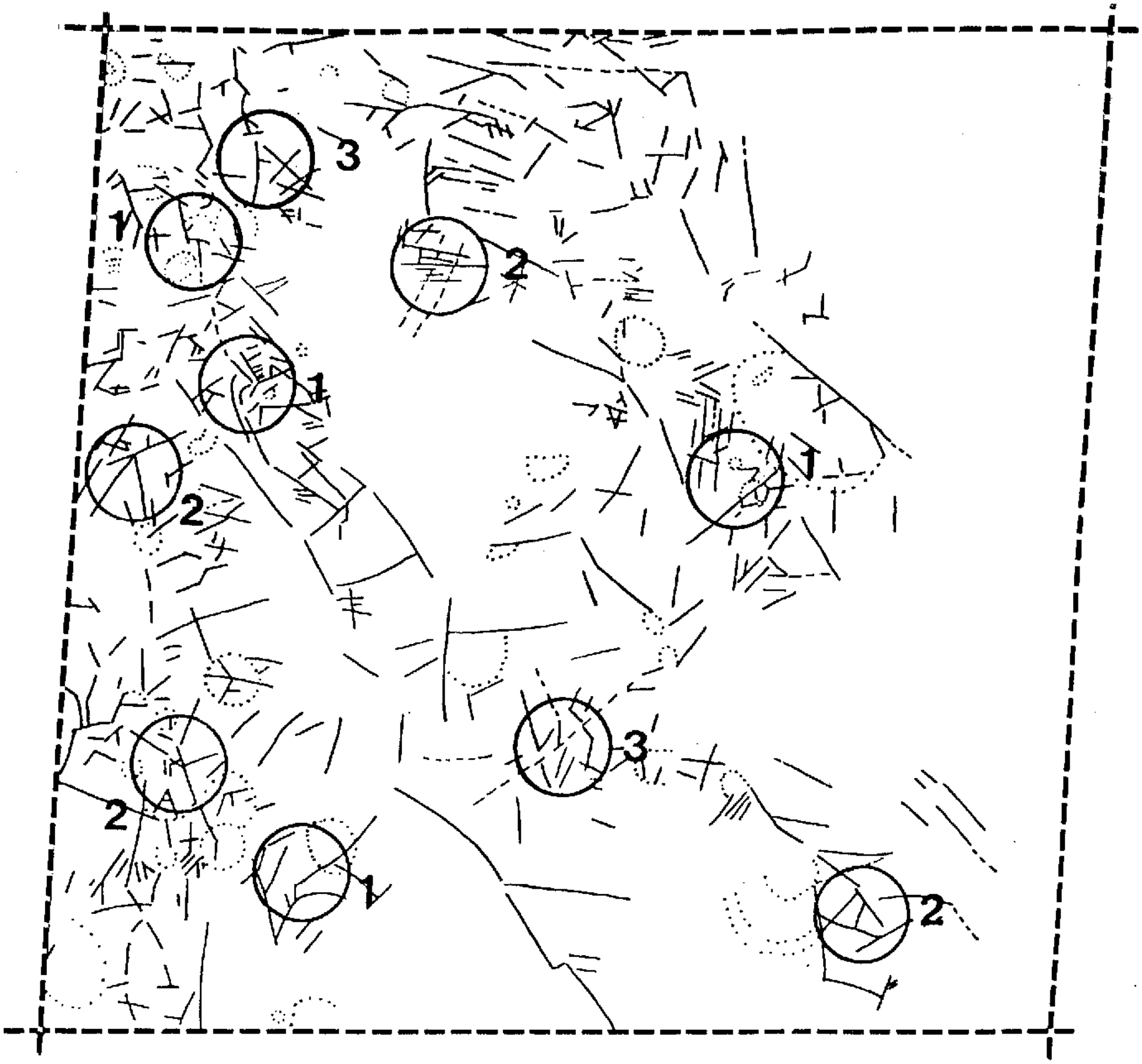

Figure 9 . Location of target areas selected on the basis of photo-linears. The priorities (1, highest, etc.) are indicated by the number next to each target area.

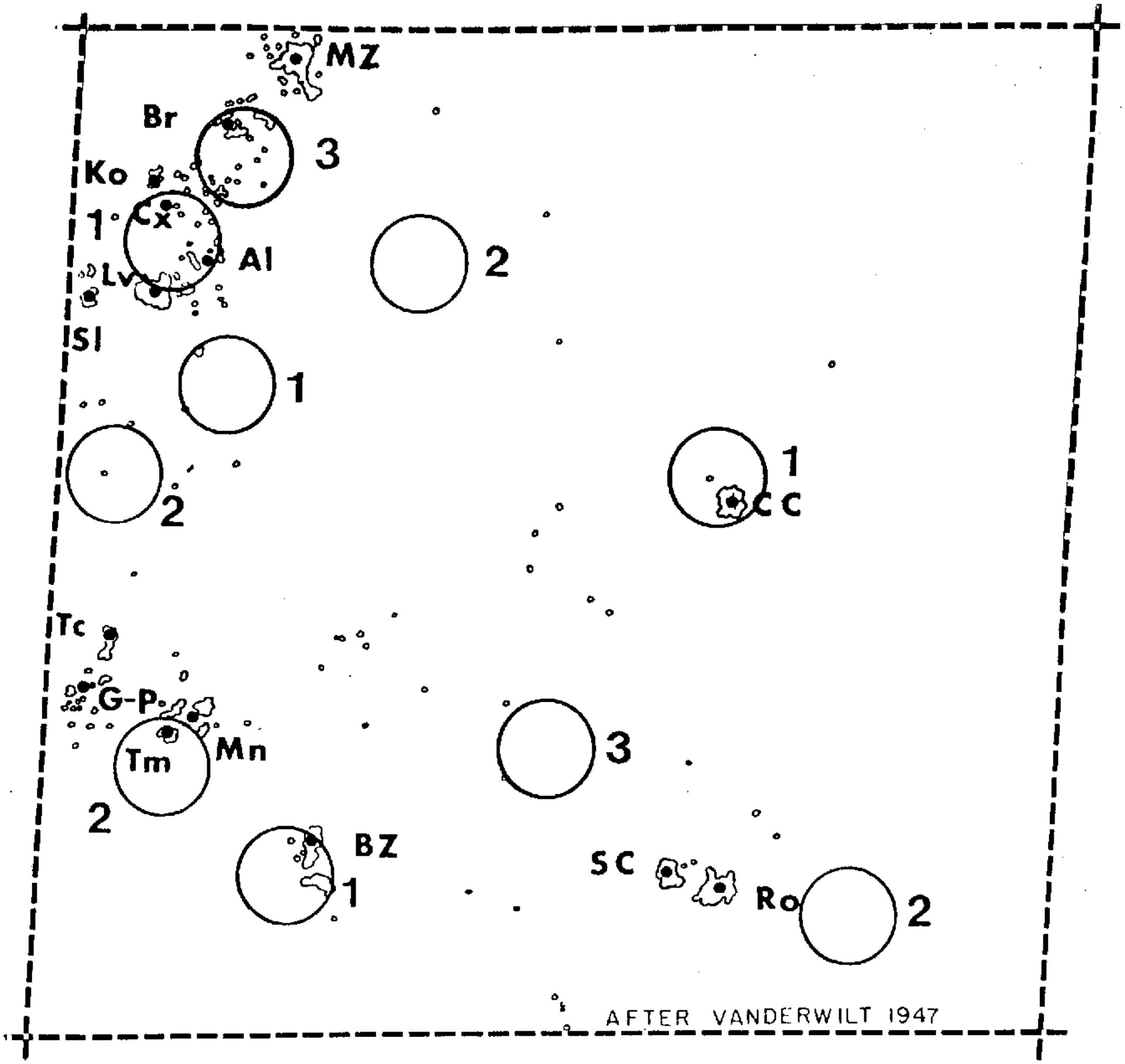

Figure 10. Location of major mineral districts and selected target areas. The small circles are isolated areas of mineral production, generally of low value. The larger mineral districts indicated by a black dot have irregular outlines and are annotated by an abbreviation: MZ-Montezuma, Br-Breckenridge, Ko-Kokomo, Cx-Climax, Al-Alma, Lv-Leadville, Sl-Sugarloaf, Tc-Tincup, G-P-Goldbrick-Pitkin, Tm-Tomichi, Mn-Monarch, BZ-Bonanza, CC-Cripple Creek, SC-Silver Cliff, Ro-Rosita.

Tomichi, Bonanza, and Cripple Creek. These results were better than expected, so the influence of prior geologic knowledge of the test area on target selection was tested.

BIAS IN TARGET SELECTION

Copies of just the lineament interpretation were distributed to a test group of 15 Colorado School of Mines professors and graduate students. After being instructed on the basic assumptions made during the selection of the Phase I target areas (those chosen in the first part of the experiment), each member of the group was asked to select 10 circular, 14 kilometer-diameter target areas. Analysis of the test group's selections (Phase II target areas) showed a remarkably strong agreement for 8 target areas, 5 of which coincide with mineral districts; 4 of these 5 were also picked during Phase I of the experiment. The test group's successful targets (i.e. coincidence with a mineral district) are tabulated and compared with the successful Phase I targets in Table 3. There is a fairly strong agreement among members of the test group for the target areas that outline the following mineral districts: the Leadville-Climax-Alma area, Tomichi, Monarch, Bonanza and Cripple Creek districts.

Statistical analysis was used to evaluate both the test group's results and the method of target selection used

TEST GROUP RESULTS

MINERAL DISTRICTS	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	%
MONTEZUMA																	
BRECKENRIDGE												X				0	13
KOKOMO				X	X	X							X		X		31
CLIMAX	X			X	X	X	X	X		X	X		X	X	X	0	75
LEADVILLE	X		X	X	X	X	X	X	X	X	X			X		0	75
ALMA	X		X	X	X	X	X	X		X	X		X	X	X	0	81
SUGARLOAF																	
TINCUP									X								6
GOLDBRICK-PITKIN					X												6
TOMICHI			X		X	X		X			X	X		X	X	0	56
MONARCH	X	X			X	X	X			X				X			44
BONANZA	X					X	X	X		X				X		0	44
SILVER CLIFF																	
ROSITA																	
CRIPPLE CREEK			X	X		X	X	X	X	X		X	X	X	X	0	75

Table 3. Test group's successful target areas. Each letter across the top corresponds to a member of the test group. Coincidence of a mineral district with a target area is indicated by the letter X. The letter O in column P represents the successful target area selections of Phase I. The last column indicates the percent agreement for successful target areas selected during Phase I and Phase II of the experiment.

in the experiment. The probability of selecting one successful target area in ten tries by random process is .32; this value decreases to .01 for selecting five successful target areas. In addition, the probability of 5 people choosing the <u>same</u> successful target area by random process is a mere 1.4×10^{-7}. The analysis was performed by placing a square grid with the approximate dimensions of a target area (9-x9-mile squares) on the lineament interpretation and the mineral district overlays. The probabilities were calculated assuming that there are 12 chances for a target area to coincide with a mineral district and there are 70 possible choices (target areas-squares) which coincide with photo-lineaments occurring on the overlay.

Analysis of the test group's results indicate that bias had very little, if any, effect on the selection of the Phase I target areas, and suggests that some of the mineral districts are defined by photo-lineament information.

PHOTO-LINEAMENTS AND MINERAL DISTRICTS

To determine what relationships exist between mineral districts and photo-linears, the frequency of photo-lineament intersections was plotted using a computer program originally designed to plot stereonet data in a form suitable for contouring. The contoured plot shows the density, or concentration, of all types of intersections on the photo-lineament overlay (Fig. 11).

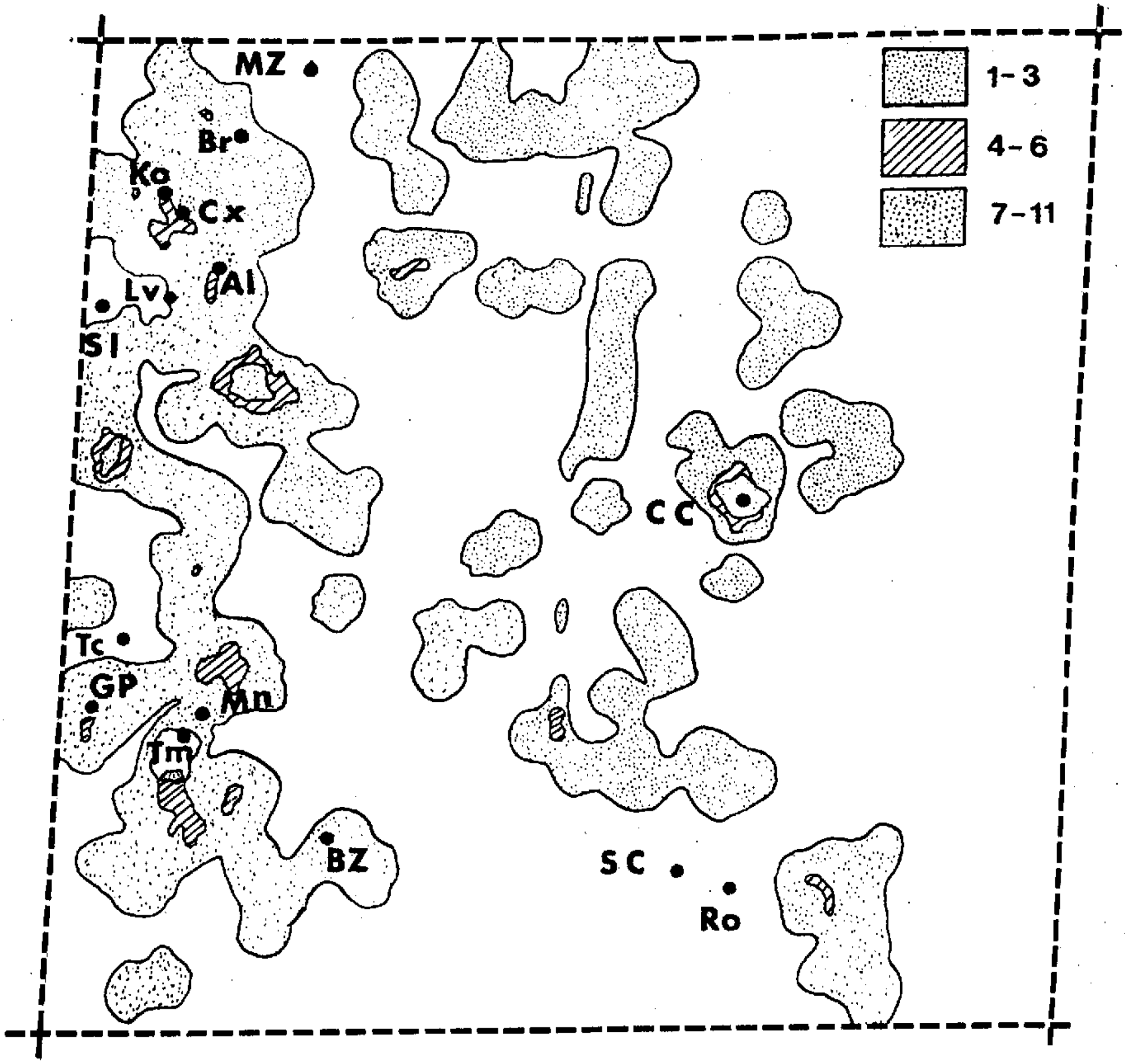

Figure 11. Density of photo-lineament intersections and the location of major mineral districts. The numbers in the legend represent the number of photo-lineament intersections per unit area.

The Cripple Creek district is well defined by a high density of lineament intersections, and the Kokomo, Climax-Alma, Goldbrick-Pitkin and Tomichi districts are moderately-well defined. The Leadville and Bonanza districts were not discriminated by this method. It should be noted that the Kokomo and Goldbrick-Pitkin districts do not coincide with the previously-selected Phase I target areas, but they are discriminated by a high density of photo-lineament intersections. It is also interesting to note that the 8 target areas that show good agreement among members of the test group, also coincide with areas having a high concentration of lineament intersections.

SUMMARY

A promising approach to the selection of mineral exploration targets using ERTS imagery has been demonstrated. This study reduced an original search area of 33,500 sq km (13,000 sq miles) to ten 165 sq km (64 sq mi) reconnaissance target areas that appear to have the structural relationships commonly associated with mineralization in this region. Major mineral districts exist in 5 of the 10 target areas selected. In addition, this experiment shows a definite correlation between some of the major mineral districts in this part of Colorado and areas having a high density of photo-lineament intersections as interpreted from ERTS imagery.

CONCLUSIONS

The results of this experiment suggest that photo-lineaments on ERTS imagery are fractures or fracture-controlled features and that their distribution may be a guide to metallic mineral deposits in Colorado, and probably other areas as well. Analysis of photo-lineament information contained on ERTS imagery can be a very valuable and inexpensive first step in any mineral exploration program, especially if it is used in conjunction with other sources of geologic information. Imagery acquired from space will probably prove most useful in areas of the world in which less is known about the geology. Moreover, the favorable results of this study suggest that those target areas that do not correspond with <u>known</u> areas of mineralization may, in fact, be new targets for mineral exploration in Colorado.

ATMOSPHERIC EFFECTS

The Colorado School of Mines is participating in a cooperative study aimed at determining the effects of the atmosphere on ERTS MSS imagery. This research is being conducted by scientists at the Martin Marietta Corporation under subcontract to the Colorado School of Mines, and in cooperation with the Environmental Research Institute of Michigan (ERIM) and Dr. Harry Smedes of the U.S. Geological Survey. The Colorado School of Mines portion of this cooperative study consists basically of the following:

1. Spectral measurements of direct, diffuse, and total solar radiation in the ERTS MSS bands.
2. Spectral reflectance measurements on selected broad outcrops in central Colorado.

This data will be used by the ERIM to re-calculate the radiance recorded by the MSS and to thereby generate atmospherically-corrected MSS tapes. Dr. Smedes will evaluate the utility of atmospherically-corrected ERTS data by comparing computerized terrain recognition maps generated with corrected and non-corrected MSS data.

The Colorado School of Mines has completed its data collection and has passed the data on to the others for study and evaluation.

GROUND SUPPORT DURING SATELLITE OVERPASS

Two field crews were on station during the 17 May 1973 ERTS-1 overpass. Hazy, thin cirrus clouds began appearing over both the Granite Hills and Cross Creek stations about 0715 and continued progressively more dense. Finally, at about 1100 MDT a heavy, solid cloud cover appeared overhead, rendering solar radiation data at time of ERTS overpass completely useless.

The same two stations were again occupied for the 21 June 1973 overpass. An ISCO Spectroradiometer was used on each site with excellent results. The best data, by far, of any obtained at time of ERTS overpasses were recorded at both Granite Hills and Cross Creek on this date. Measurements consisted of a repeating series of the following data, recorded spectrally from 4000 to 1100 nanometers:

A) Direct solar radiation

B) Total solar radiation as viewed through a BG-36 filter for instrument calibration purposes

C) Diffuse solar radiation

D) Hemispherical reflectance (180°) of the outcrop

3) Directional reflectance of a spectrally-calibrated white card

F) Directional reflectance of the outcrop

G) Directional reflectance of a spectrally-calibrated gray card.

An ISCO spectroradiometer was used on each of the two sites to derive the above measurements. A Bendix Model 100 Radiant Power Measuring Instrument (RPMI) was used to derive optical depth. Such measurements are required in order to determine the effects of the atmosphere on the ERTS MSS data and to derive sensor corrections to be performed by the Environmental Research Institute of Michigan (ERIM). The radiance recorded by the ERTS MSS is related to the above measurements by

$$N_{MSS} = \frac{\rho \; He^{-\tau \sec \theta_o}}{\pi} + N_p$$

where ρ is the target reflectivity, H is the total solar radiation, τ is optical depth, N_p is the atmospheric path radiance, and θ_o is the solar zenith angle. As discussed previously, H and τ were measured, along with ρ. The path radiance, N_p, will be calculated by ERIM. This will then allow the ERTS data to be corrected for atmospheric effects, and subsequent evaluation (by H. Smedes of USGS) of these effects on computerized terrain recognition routines.

The results of the measurements are shown in Figures 12 through 17, and in Table 4. The Granite Hills site had a slightly higher amount of total solar radiation which is most likely a result of the slightly higher ratio of diffuse to total solar radiation. The optical depths at the two

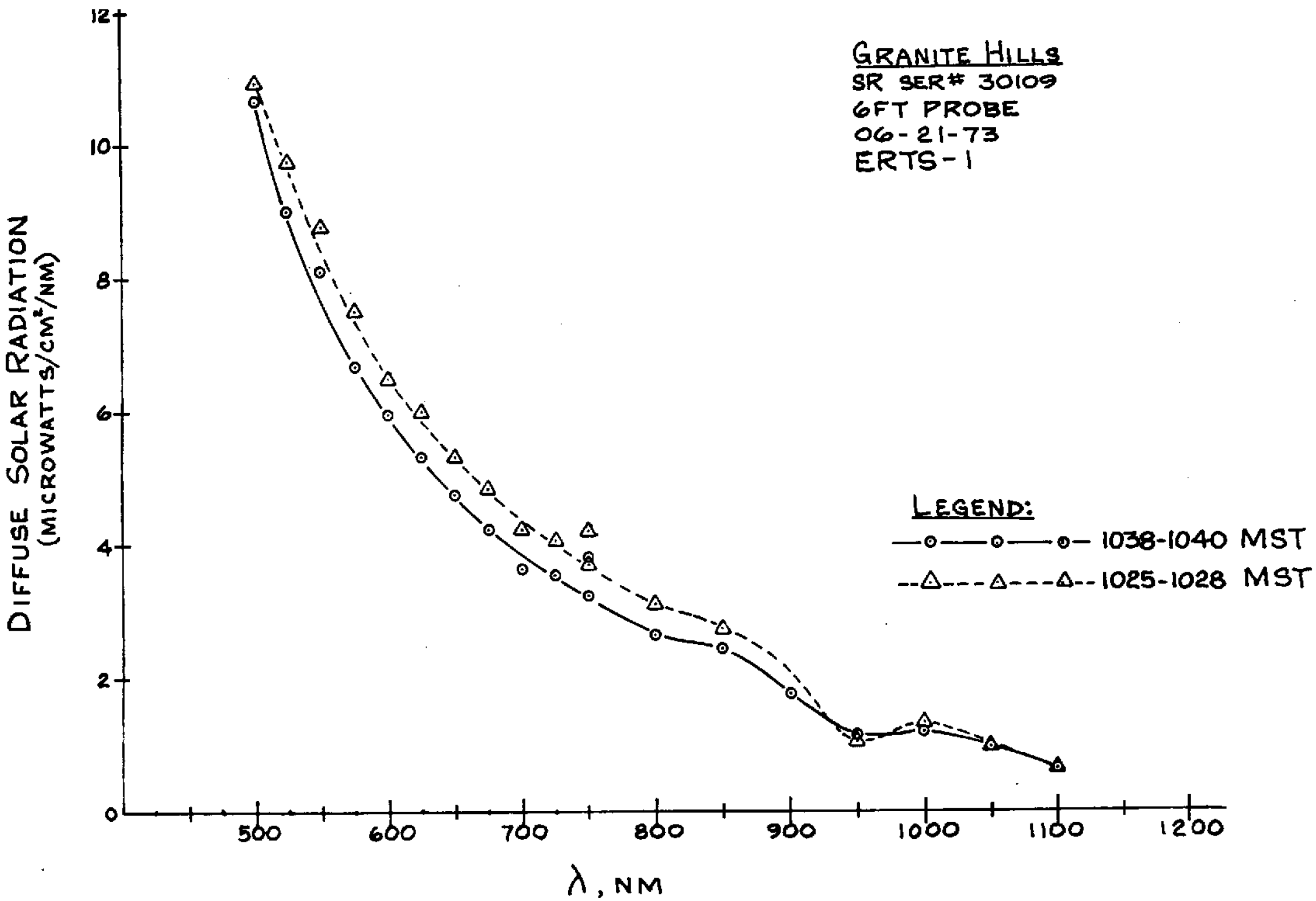

Figure 12. Diffuse Solar Radiation Incident on Granite Hills Test Site (Pikes Peak Granite) 21 June 1973

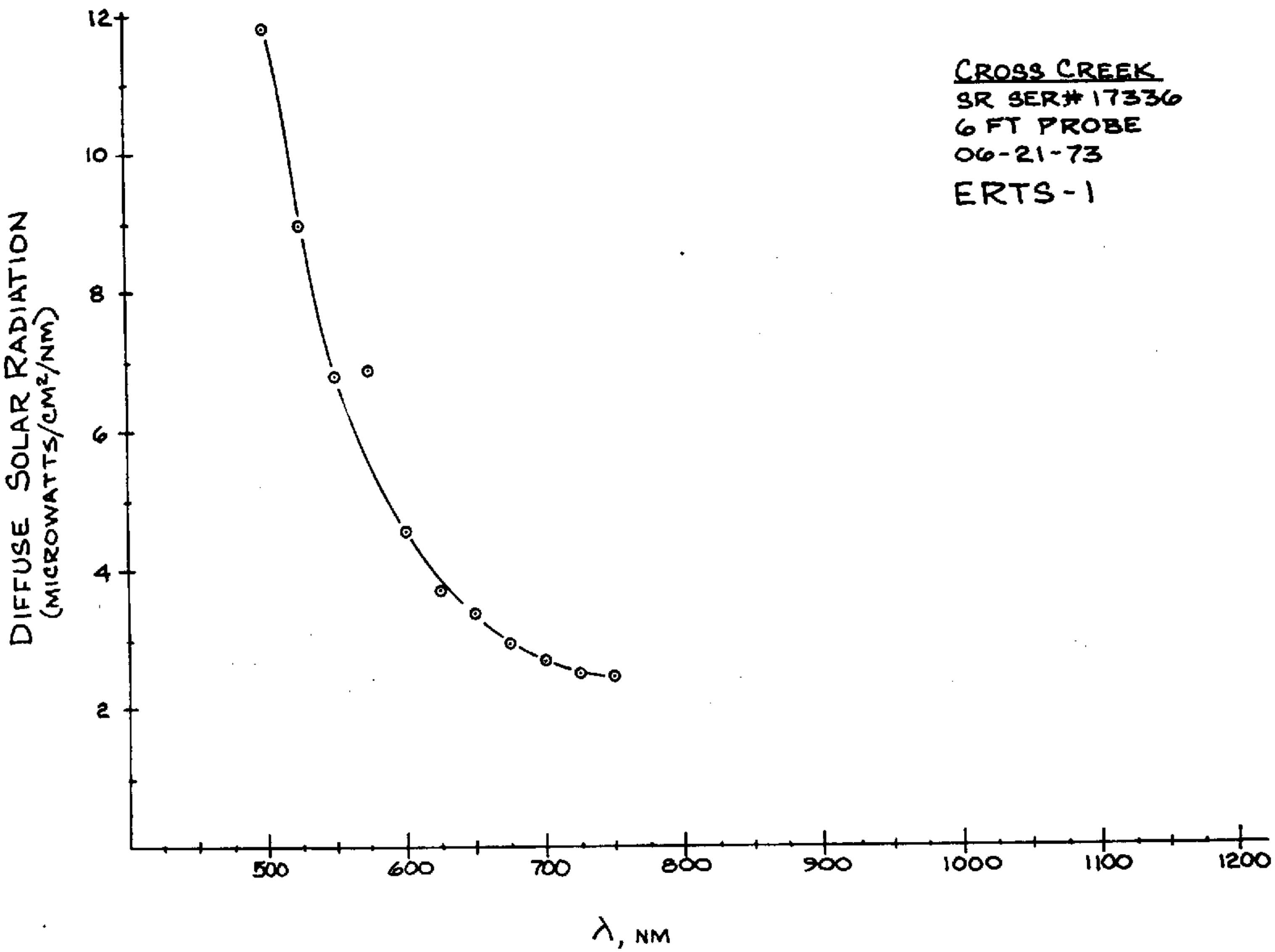

Figure 13. Diffuse Solar Radiation Incident on Cross Creek Test Site (Thirtynine-Mile Basalt) 21 June 1973

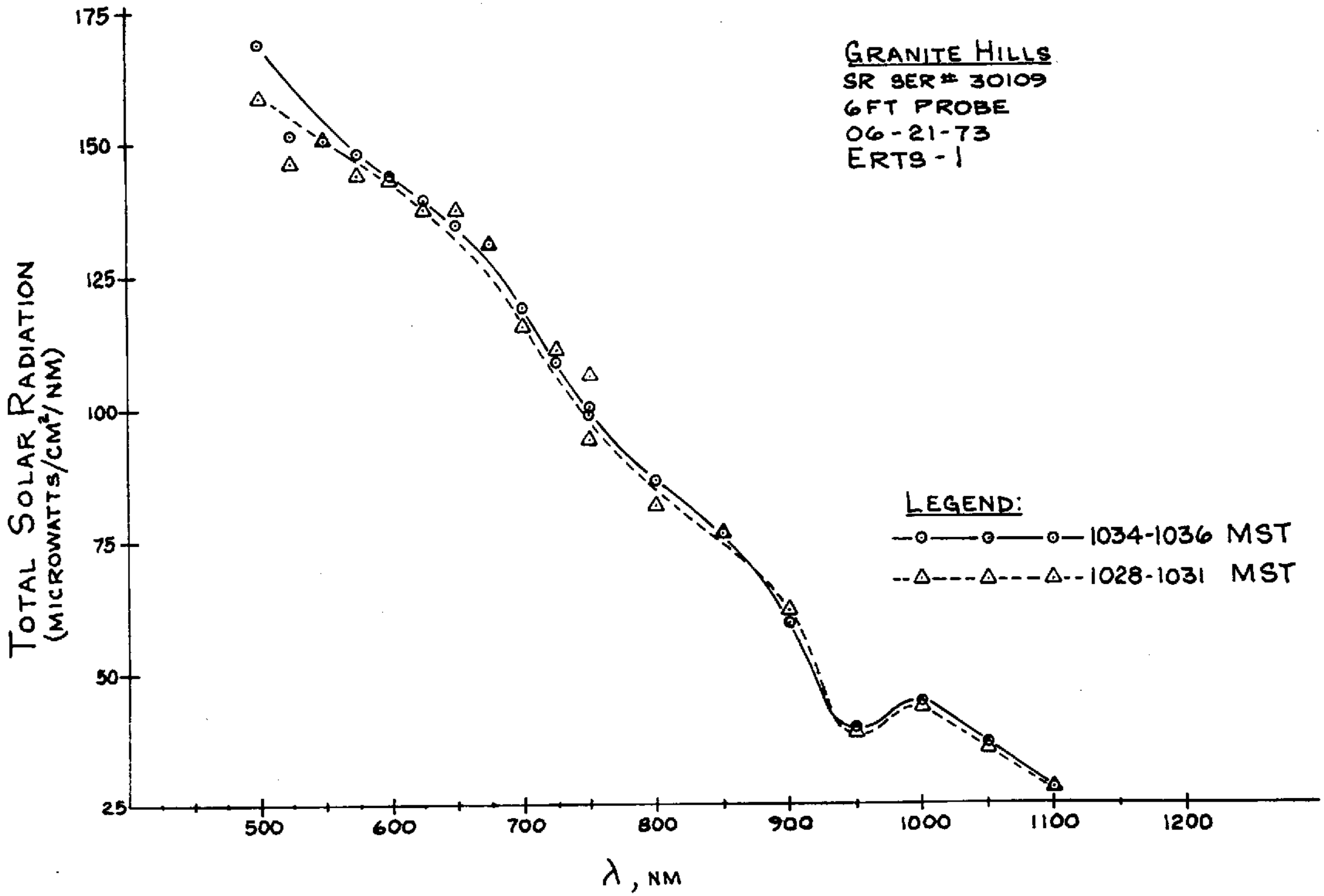

Figure 14. Total Solar Radiation Incident on Granite Hills Test Site (Pikes Peak Granite) 21 June 1973

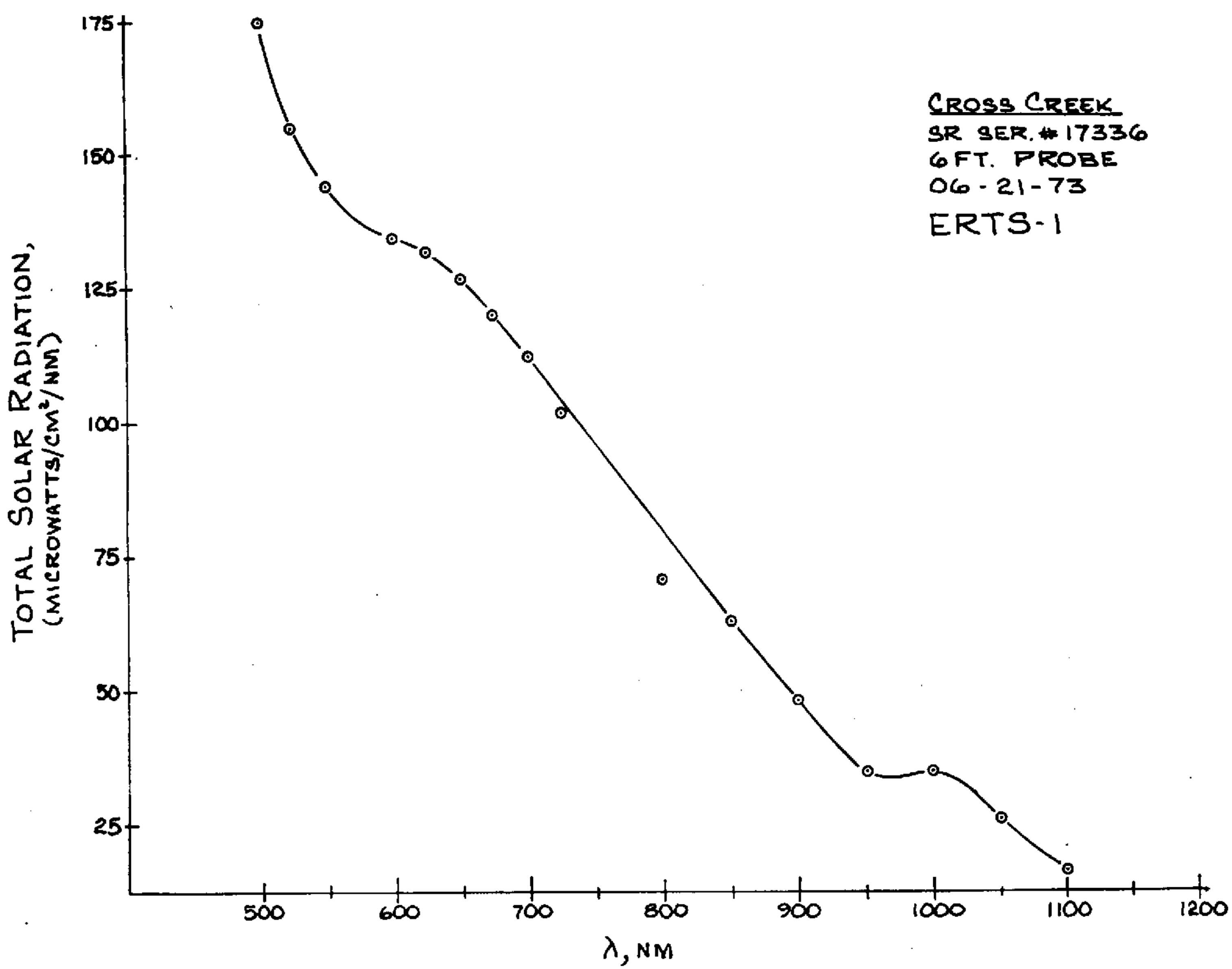

Figure 15. Total Solar Radiation Incident on Cross Creek Test Site (Thirtynine-Mile Basalt) 21 June 1973

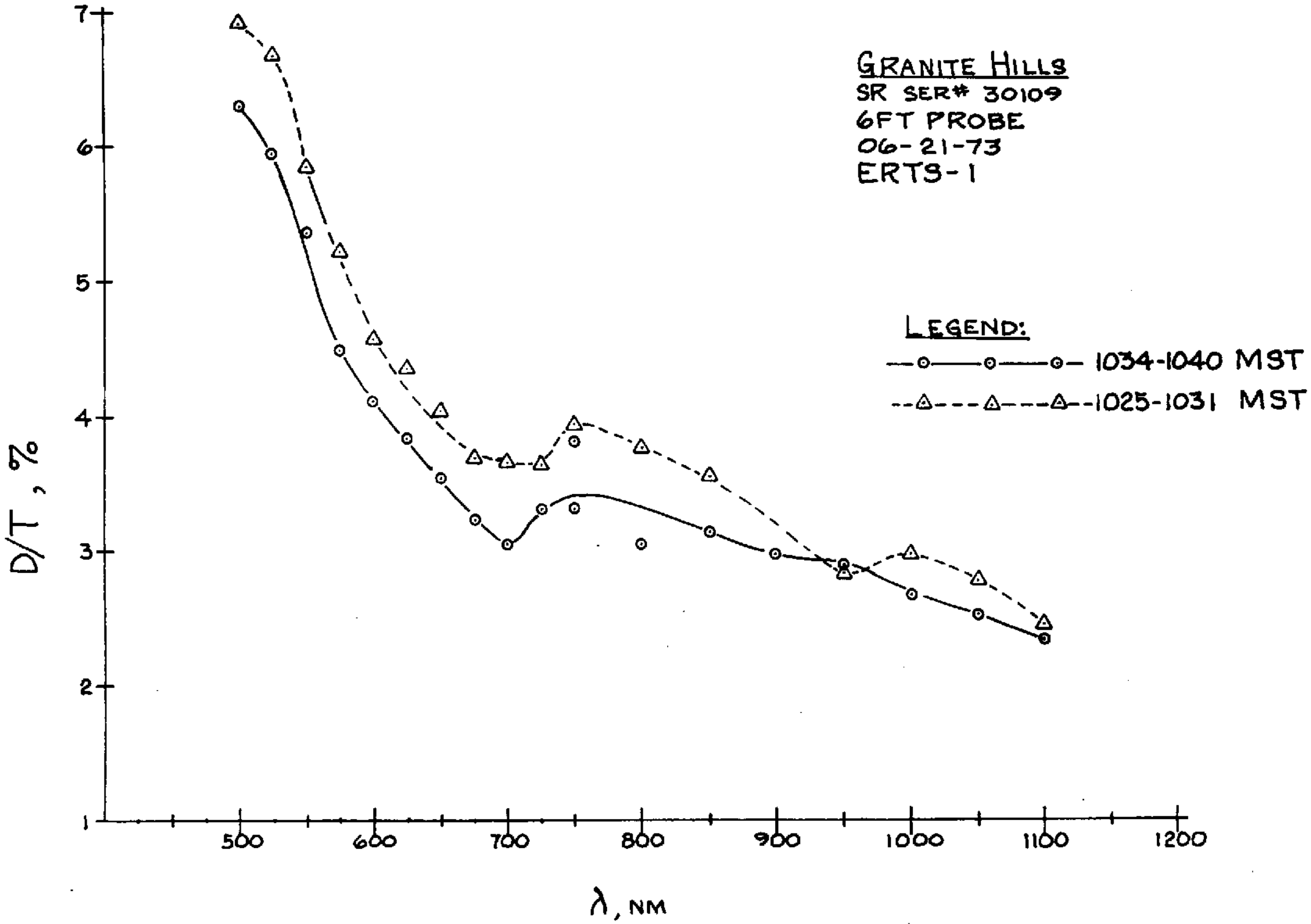

Figure 16. Ratio of Diffuse-to-Total Solar Radiation Incident on Granite Hills Test Site (Pikes Peak Granite) 21 June 1973

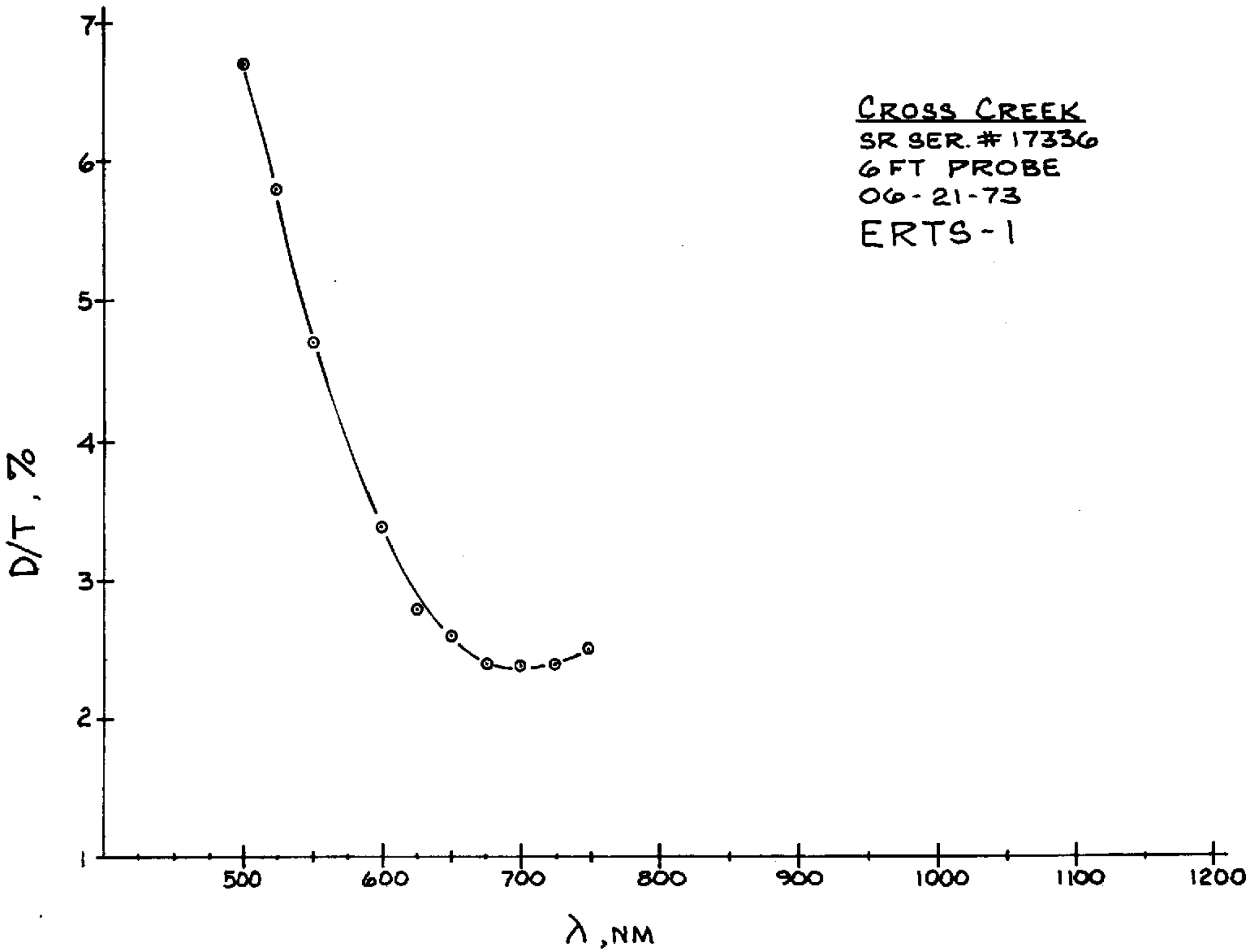

Figure 17. Ratio of Diffuse-to-Total Solar Radiation Incident on Cross Creek Test Site (Thirtynine-Mile Basalt) 21 June 1973

Table 4. Optical Depth Measurements at Two Locations Using Bendix Model 100 RPMI; 6-21-73

Cross Creek: Time - 1154 MST, Sec θ_o = 1.04
Elevation: 9,400 Feet

ERTS-1 MSS Bands	B1	B2	B3	B4
Meter	1.39	1.40	1.18	.862
Scale	30	30	30	10
M-Intensity	13.9	14.0	11.8	8.62
M_o	16.4	15.9	12.8	9.15
τ	.159	.122	.078	.058

Granite Hills: Time - 1030 MST, Sec θ_o - 1.10
Elevation: 8,240 Feet

ERTS-1 MSS Bands	B1	B2	B3	B4
Meter	1.38	1.39	1.17	.853
Scale	30	30	30	10
M	13.8	13.9	11.7	8.53
M_o	16.4	15.9	12.8	9.15
τ	.157	.122	.082	.063

sites are similar. The optical depth is calculated by

$$\tau = \frac{\ln M_0 - \ln M}{\sec \theta_0}$$

where M is intensity as measured by the RPMI for each ERTS band, and M_0 is the calculated intensity that would be measured by the RPMI outside of the atmosphere. M_0 was determined using data from the ERTS overpass of 16 February 1973. M_0 is calculated by taking several intensity readings at varying airmasses (sec θ_0). Intensity, M, is plotted (semi-log) vs. airmass, sec θ_0 (linear axis) to extrapolate M_0 to an airmass of zero intensity outside of the atmosphere.

The June 21 data will be analyzed in more detail along with the February 16 data and the anticipated July 10 data. Figure 18 compares the spectral reflectance of the two test sites as seen by the ISCO spectroradiometer, and at one site as seen by the RPMI.

SPECTRAL REFLECTANCE USING BENDIX RPMI

In addition to the measurements of solar radiation and rock reflectivity described above, a Bendix RPMI was used to record spectral reflectivity in each of the four ERTS-1 bands at a number of field outcrop locations. These outcrops included; Pikes Peak Granite, Cripple Creek Granite, mine tailings at the Mollie Kathleen gold mine at Cripple Creek,

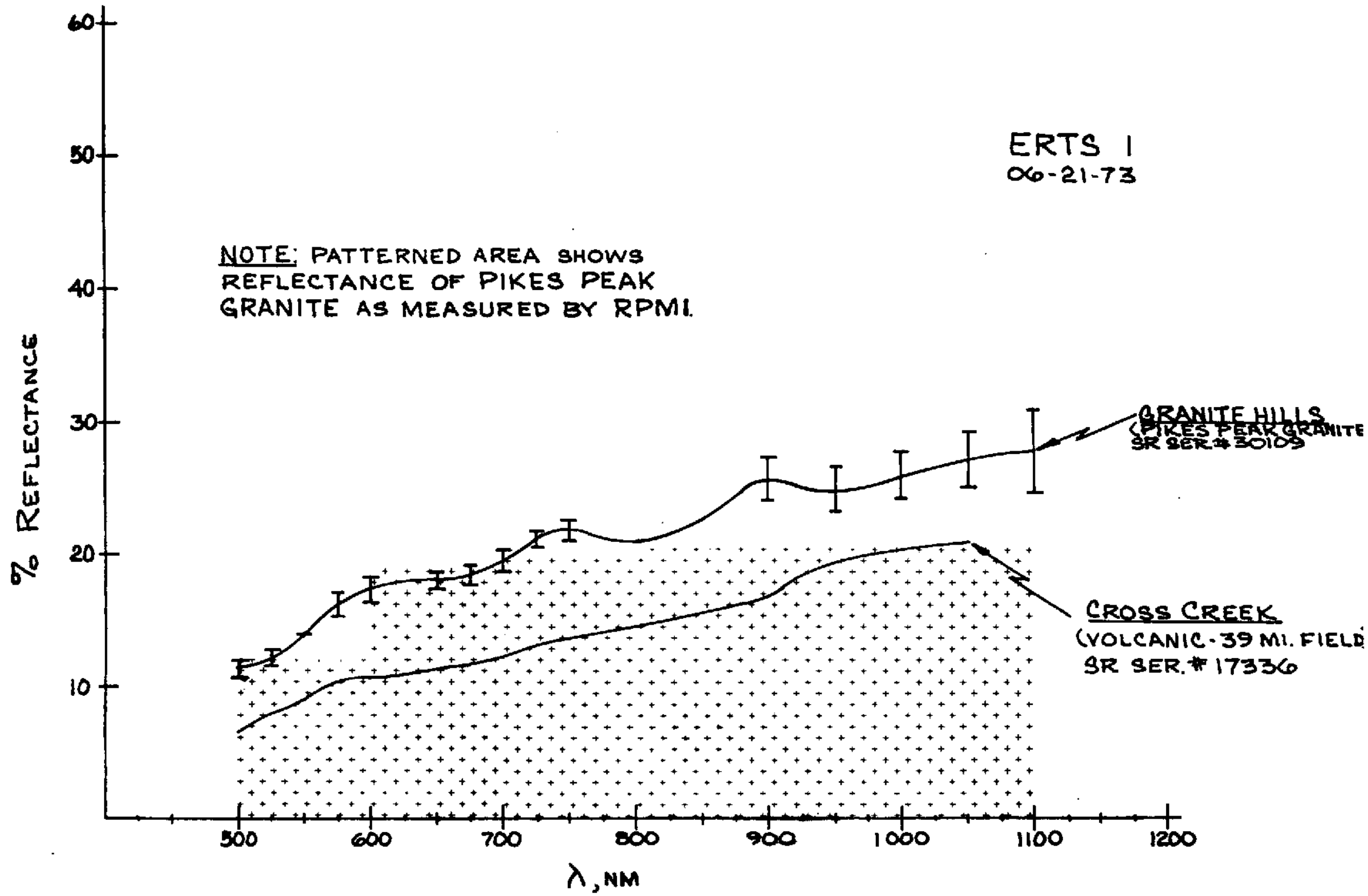

Figure 18. Comparison of Spectral Reflectance of Pikes Peak Granite and Thirtynine-Mile Basalt, 21 June 1973

undisturbed, altered Cripple Creek granite near the mined area, sandstones of the Dakota formation and Carlisle shale (Table 5).

During all of these measurements, the Bendix RPMI worked flawlessly, was extremely portable and easy to use, and it produced consistently good data. Use of an instrument of this type is recommended for future ERTS spectral reflectivity studies.

Table 5. Percent Reflectance Relative to MgO of Typical Rock Outcrops As Measured With Bendix Model 100 RPMI, 6-20-73 And 6-21-73

Outcrop	B1	B2	B3	B4
Pikes Peak Granite	14.2	19.0	21.0	21.2
Cripple Creek Granite	14.5	15.9	22.2	25.3
Altered Cripple Creek Granite*	14.0	20.0	26.0	28.0
Thirtynine-Mile Basalt	10.0	13.8	16.5	18.0
Carlisle Shale	45.0	50.0	53.8	56.0
Dakota Formation	32.0	40.0	37.9	51.0
Mollie Kathleen Mine Tailings*	19.0	30.0	50.0	34.0

*Taken under poor lighting

SUPPORTING FIELD WORK

During June, July, and August of 1973, field investigations were conducted in order to obtain ground information that would help in evaluating the basic geologic information in ERTS imagery of Colorado. The field studies covered portions of the Leadville mining district in the Mosquito Range and the Silverton-Ouray and south Ophir districts in the San Juan Mountains. Geologic maps showing the location and distribution of major rock-stratigraphic units and faults and shear zones were prepared at a scale of 1:24,000. Particular attention was payed to locating and mapping mineralized and non-mineralized fractures and veins and areas of hydrothermal alteration.

Work is now in progress to study the field areas on supporting aircraft photography and ERTS imagery. The goal of this work is to determine how well local manifestations of mineralization may be located or interpreted from remote sensing data and, in particular, to determine whether the regional overview provided by ERTS imagery can be effectively applied to mineral exploration.

PROGRAM FOR NEXT REPORTING PERIOD

During the next reporting period, emphasis will continue to be placed on the geologic interpretation and methods of utilization of ERTS-1 imagery and supporting aircraft data. The primary goals of ERTS-1 imagery analysis will be: (1) To determine the type, scale, and identifying characteristics of the geologic phenomena that can be identified from ERTS imagery alone or in combination with aircraft and ground data, (2) To determine which spectral bands are best suited for general and specific geologic studies in Colorado, (3) To evaluate further such factors as time of year, sun angle, snow cover, etc., and their effect on geologic interpretability of ERTS imagery, (4) To further investigate and develop the various interpretive techniques available for ERTS imagery, and (5) To further develop techniques for using the results of geologic interpretation of ERTS data.

NEW TECHNOLOGY

No new technology was developed during the time period covered by this report.

CONCLUSIONS

ERTS imagery of central and western Colorado contains an extraordinary amount of basic geologic information. Most of this information can be extracted by standard photo-geologic interpretation techniques, without the use of expensive and sophisticated laboratory equipment. This is fortunate since high-powered data processing facilities are not generally available to those geologists who will ultimately be the largest users of ERTS imagery--practicing geologists affiliated with government, industry, or a university.

The largest task now facing geologists is to learn how to best apply ERTS imagery for finding solutions to specific geologic problems. During this investigation, some progress has been made on using ERTS imagery for regional fracture analysis and metallic mineral exploration and, to some degree, the study of the close association between mineral deposits and volcanic phenomena.

RECOMMENDATIONS

Although the geologic framework of central and western Colorado does not change significantly from season to season or from year to year, repetative coverage by the ERTS satellite is highly desirable because seasonal changes in 1) solar elevation and azimuth angle, 2) snow cover, 3) vegetation growth vigor, and 4) surface water runoff act to enhance different geologic phenomena. Therefore, in order to extract the maximum amount of geologic information from a given scene, ERTS imagery from several different times of year should be analyzed.

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