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BONANZA PROJECT - 1971

by

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INTRODUCTION

This paper presents a review of the activities of the Colorado School of Mines on the Bonanza Project. Activities prior to 1971 are included in this review only in a general way; activities during 1971 are discussed in detail.

The Bonanza Project is a joint effort of the Colorado School of Mines (CSM) and the Martin Marietta Corporation (MMC). CSM brings to this effort faculty and graduate students with recognized ability in the geological sciences, while MMC has demonstrated competence in aerospace technology. This combined capability then, working together with the same data from different approaches, attempts to maximize the extraction of geologic information from remote sensor data.

The Bonanza Project began in 1969 with a grant from the Office of University Affairs (OUA). Since that time, support has come jointly from both OUA and the Earth Resources Survey Program Office, under NASA Grant NGL 06-001-015. Dr. Arch Park is technical monitor of this grant.

The objectives of the Bonanza Project are twofold: (1) to develop an educational program of graduate study in geologic remote sensing, and (2) to conduct research on the applications of remote sensing to the mineral industry.

EDUCATIONAL PROGRAM

COURSES OFFERED

Faculty working under this grant have developed three graduate courses in geologic remote sensing:

Introduction to Remote Sensing
Geologic Applications of Remote Sensing
Seminar in Geologic Remote Sensing

The first course in this series, Introduction to Remote Sensing, deals with the theory of active and passive remote sensing systems, using the energy path concept in the ultraviolet through radar portions of the electromagnetic spectrum. Students are introduced to remote sensing instruments and the interpretation of representative data. Geologic applications are briefly surveyed.

To date, this course has been offered four times, twice as part of the CSM Continuing Education Program, which made the class available to practicing scientists and engineers in the Denver metropolitan area. Combined enrollment has totalled 46 students, including undergraduates, graduate students and professional scientists and engineers.

The second course, Geologic Applications of Remote Sensing, stresses the application of remote sensing to geologic and mineral resource investigations. The course includes detailed study of remote sensing techniques, with field and laboratory experiments and experience in data reduction, analysis and interpretation. Case studies of demonstrated applications are presented, and potential uses are examined. Students conduct excercises in mission planning and selection of optimum sensor systems for specific geologic targets. This course is currently being taught for the second time. Combined enrollment totals 15 graduate students.

The third course of the series, Seminar in Geologic Remote Sensing, consists of group discussions and individual student presentations on current literature and research. Enrollment in the seminar to date has totalled 13 graduate students.

GRADUATE STUDENT SUPPORT

The Bonanza Project has supported the research of seven students working toward advanced degrees. One M.S. program has been completed, one is in progress, and four Ph.D. programs are in progress.

RESEARCH PROGRAM

DATA COLLECTION

All data used in this project were acquired by NASA aircraft, either for the Bonanza Project directly, or for other investigators. Those missions flown over the Bonanza Test Site (Site 185) include all or parts of Missions 101, 105, 153, 168, and 184. Data have been collected from each of the three current MSC aircraft, the P3A, C130 and RB57.

Photographic coverage is shown in Figure 1, which is a composite of all missions to date. The quality of this photography ranges from poor to excellent, being generally good.

Non-photographic data coverage is shown in Figure 2. SLAR imagery, acquired over relatively large areas for regional geologic studies, has generally been of poor quality. Fair to excellent thermal infrared imagery, both day and night, was flown over selected smaller areas, mostly for local structural information. Line data, including infrared spectrometry, multifrequency microwave radiometry and radar scatterometry, were acquired, but have yielded little geologic information.

DATA HANDLING

Photo interpretation techniques (and associated imagery interpretation techniques) have been the main analysis techniques used. This emphasis upon the human interpreter (as opposed to automatic pattern recognition techniques) evolves from three considerations:

1) Background of researchers. With one exception, all CSM personnel are geologists, and are consequently experienced in the extraction of geologic information from aerial photographs;

2) Quality of data received. To date, the best data received from NASA aircraft missions have been color and color infrared photographs. Other very useful data have included multiband photography and thermal scanner imagery,

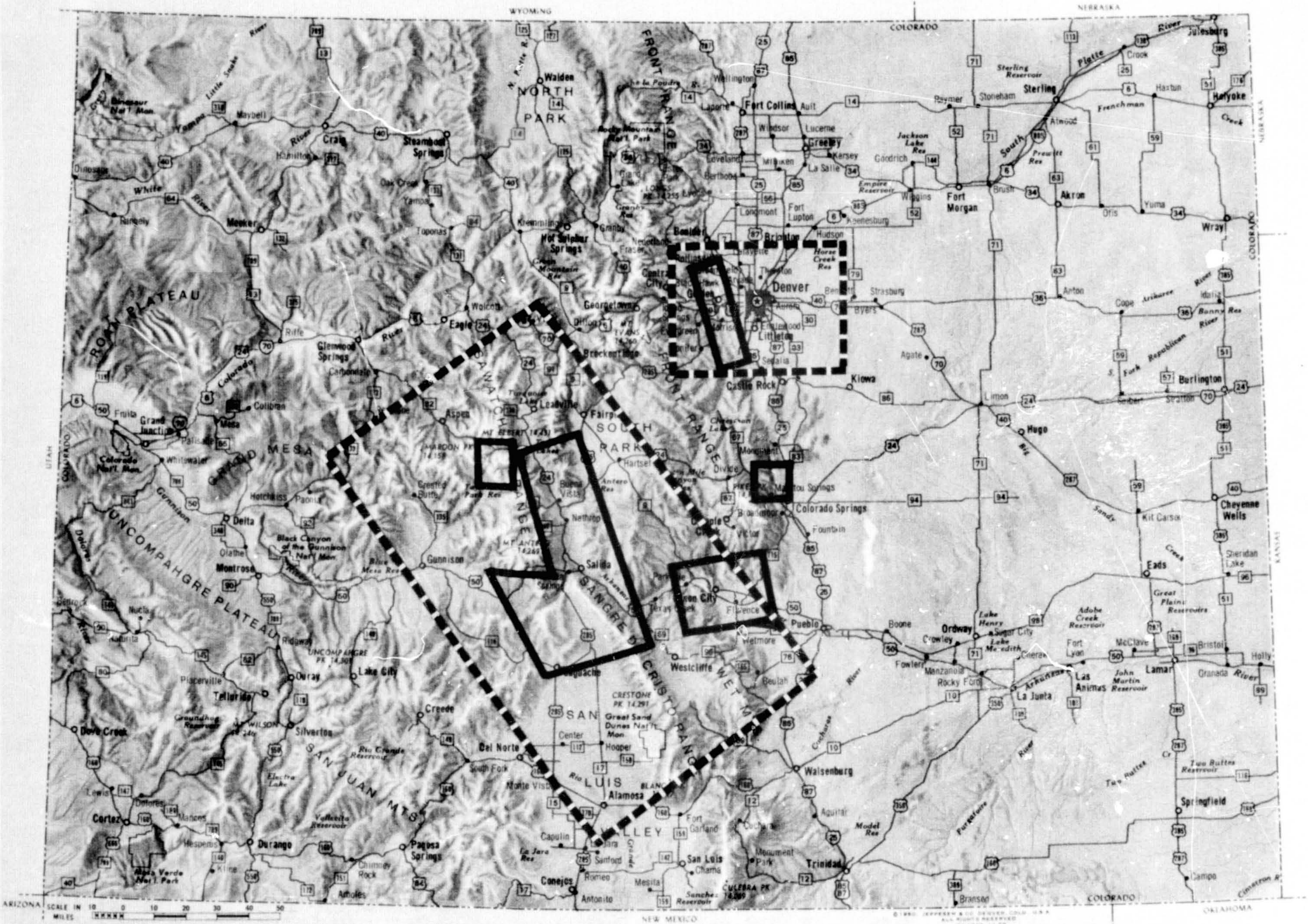


Figure 1.- Photographic coverage by NASA aircraft. Areas within dashed line are covered by small-scale (>1:100,000) photography, within solid lines the photography is large scale (<1:30,000).

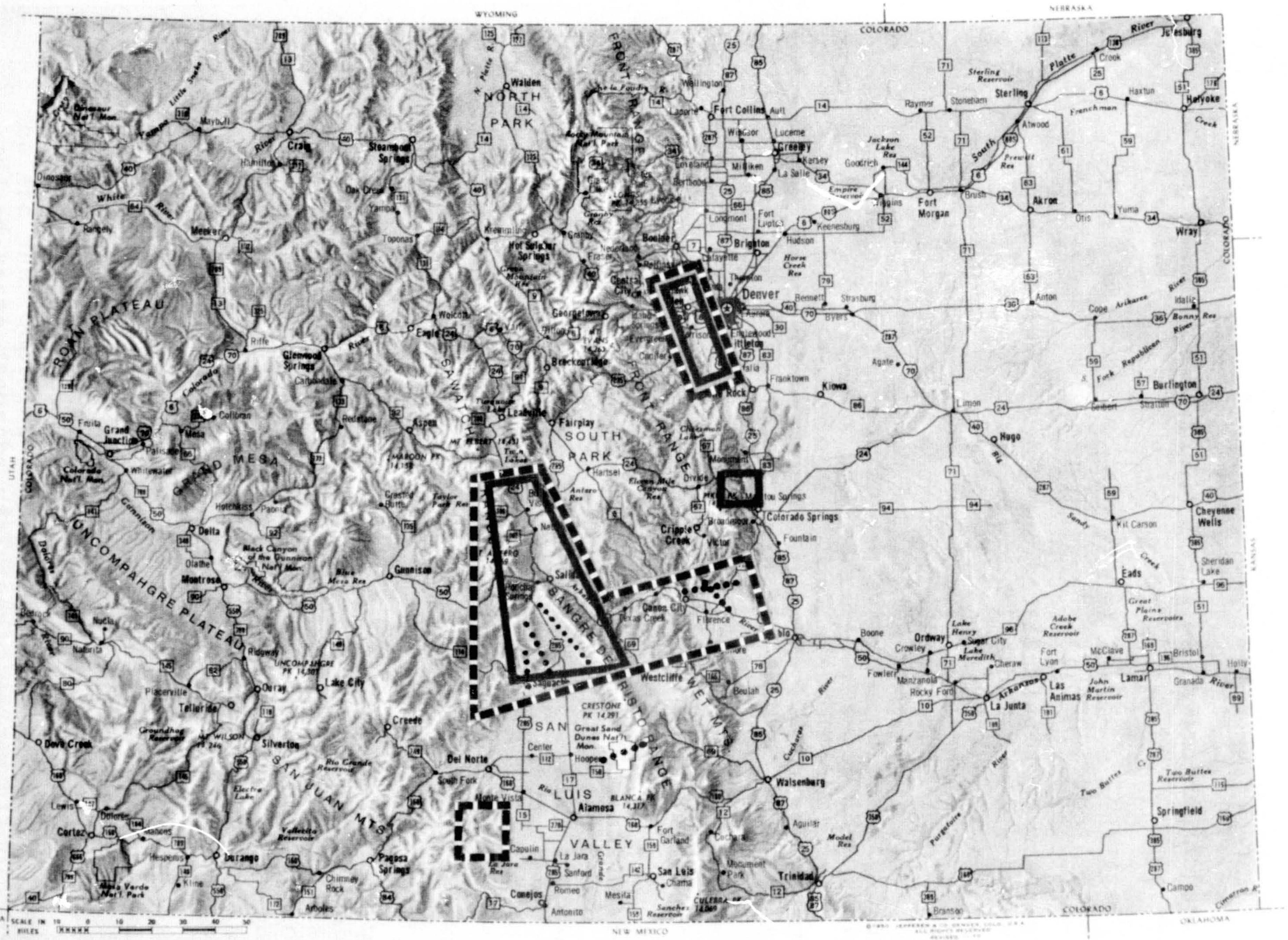


Figure 2.- Coverage by non-photographic sensors. Solid lines indicate IR scanner imagery, dashed lines are SLAR coverage, and dotted lines represent line data (microwave radiometry, radar scatterometry and infrared spectrometry).

while line data received so far have not been of good quality; and

3) Anticipated use of remote sensor data. The techniques being researched at CSM should be suitable for the average professional geologist in his work, and thus preclude reliance on sophisticated analytical instruments available only in research laboratories.

Despite the emphasis placed upon photo interpretation techniques, other data handling methods are being investigated as well, including optical and digital image enhancement, multiband color additive projection, video image processing, and computer reduction and analysis of infrared spectrometry. More detailed accounts of these interpretation techniques are discussed in the companion paper in these Proceedings by James Muhm.

GEOLOGIC APPLICATIONS

The rationale for using remote sensing for geology, as for any other discipline, is predicated on what are, by now, familiar arguments. Specifically, the remotely sensed data must provide either:

(a) new information not obtainable by other means, or

(b) a reduction in time (cost) necessary to obtain information.

New geologic information derives mainly from the synoptic view afforded by remote sensors. This "forest for the trees" situation has been used most advantageously in structural geology studies, where discontinuous surface elements are found to define a single geologic structure. Many such examples have been demonstrated, most dramatically by space photography.

The reduction in time necessary to obtain geologic information is also a recognized advantage of remote sensing, although it has not been demonstrated as well. The following example will give some indication of time-saving capability.

Figure 3 shows an area in Central Colorado that has not been geologically mapped, though the adjacent areas to the north, west and south have benn completed. This area,

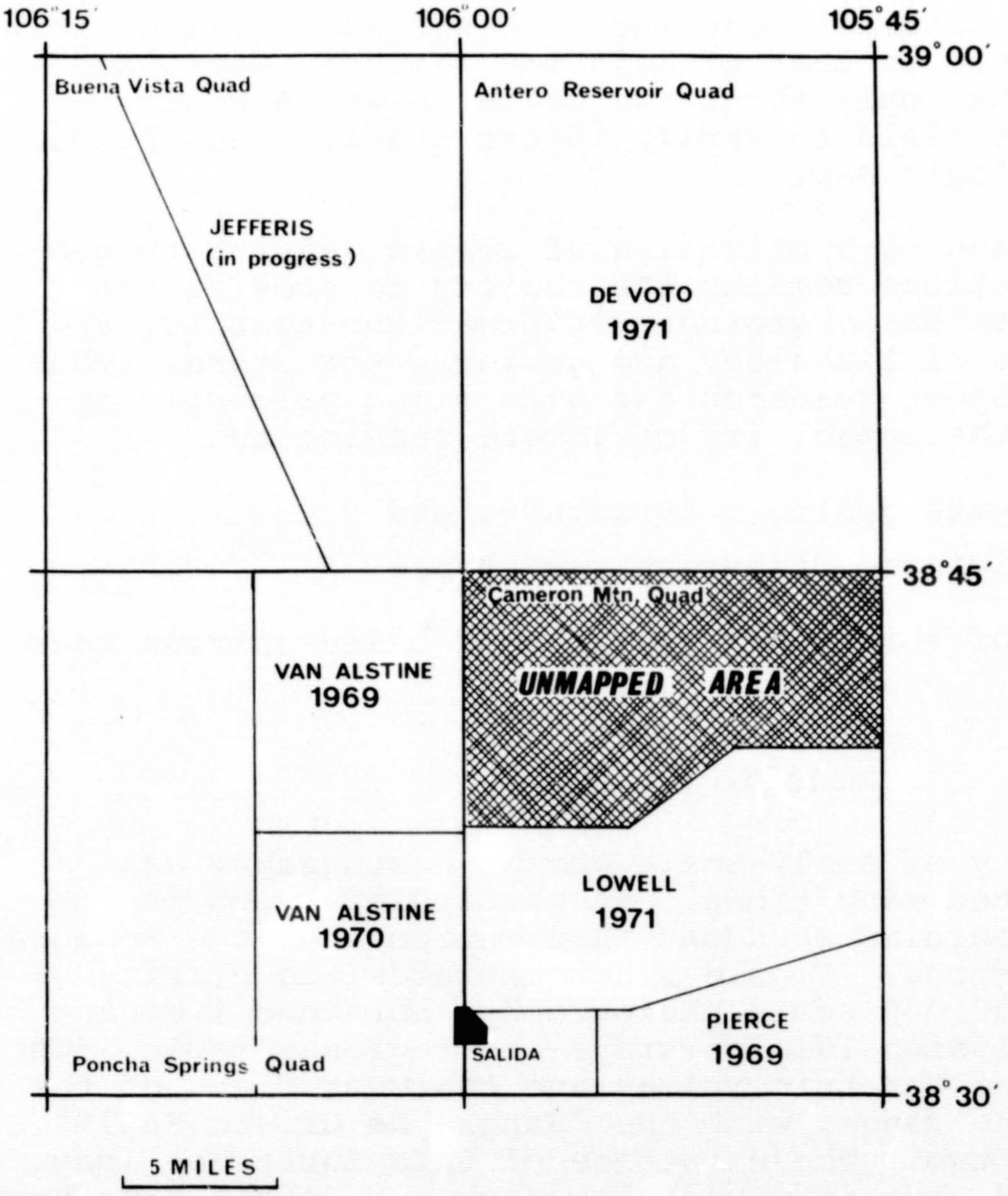


Figure 3.- Index of geologic field mapping north of Salida, Colo.

comprising about two 7½' topographic quadrangles, is typical of an area that would be assigned to a M.S. candidate for a Master's thesis, which would entail at least a full summer of field mapping. Figure 4 is a photo-geologic map produced by interpretation of NASA photography, including color, color infrared and low sun angle photography (LSAP). This study was completed by a graduate student on the Bonanza Project in approximately one week. Geologic detail of this map is comparable to that of adjacent geologic maps, and it is estimated that only about two or three weeks would be required in the field to verify interpretations and produce a finished geologic map.

The outstanding application of remote sensing to geologic investigations remains the ability to provide the interpreter with basic geologic information--that is, the surface aspects of lithology and geologic structure. Thus the Bonanza Project research has been aimed primarily at investigating the capability of remote sensing to

(1) delineate geologic structure, and

(2) discriminate different rock types.

The remainder of this paper will specifically address these two topics.

Geologic Structure

The utility of small-scale aerial photography has been demonstrated many times. In particular, such photography often contains abundant information on large regional geologic structures. Figure 5 demonstrates the clarity with which 1:100,000 scale photography, obtained from the NASA RB57 on Mission 101, portrays one regional fault. The photo covers the San Luis Valley and the west flank of the Sangre de Cristo Range, with the "Sangre de Cristo Fault" separating the two. The existance of this fault has long been postulated, but its exact location and detail have been poorly understood and the only age which could be ascribed to the fault was post-Oligocene. The synoptic view afforded by this photography allows the interpreter to join together discontinuous lineaments to synthesize one continuous fault zone, and the photos clearly show recent movement along some segments. This color IR photo has a slight advantage over regular color photography because portions of the fault line trace are marked by linear stands of aspen, which are enhanced somewhat by the IR sensitivity of this film.

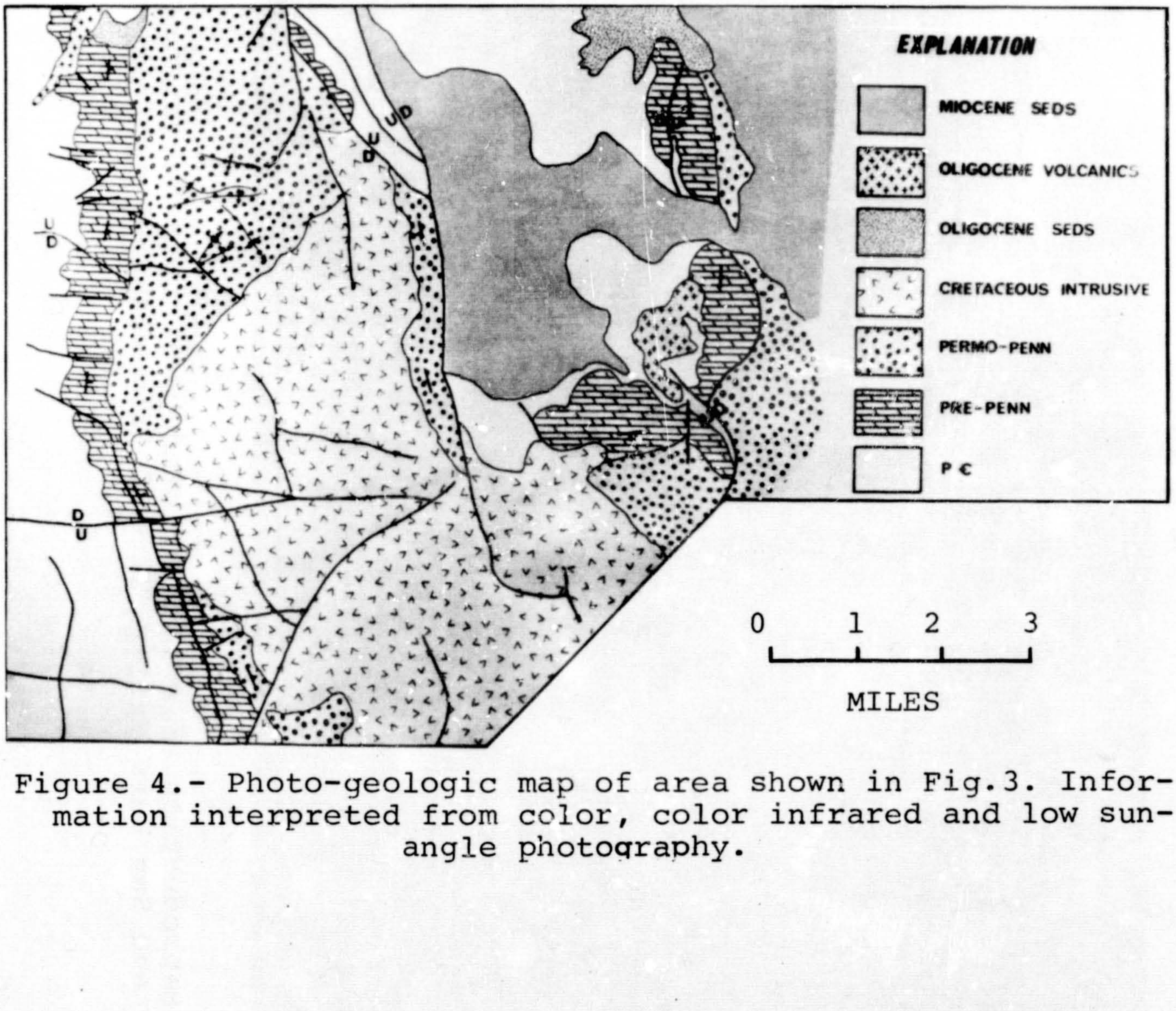


Figure 4.- Photo-geologic map of area shown in Fig.3. Information interpreted from color, color infrared and low sun-angle photography.

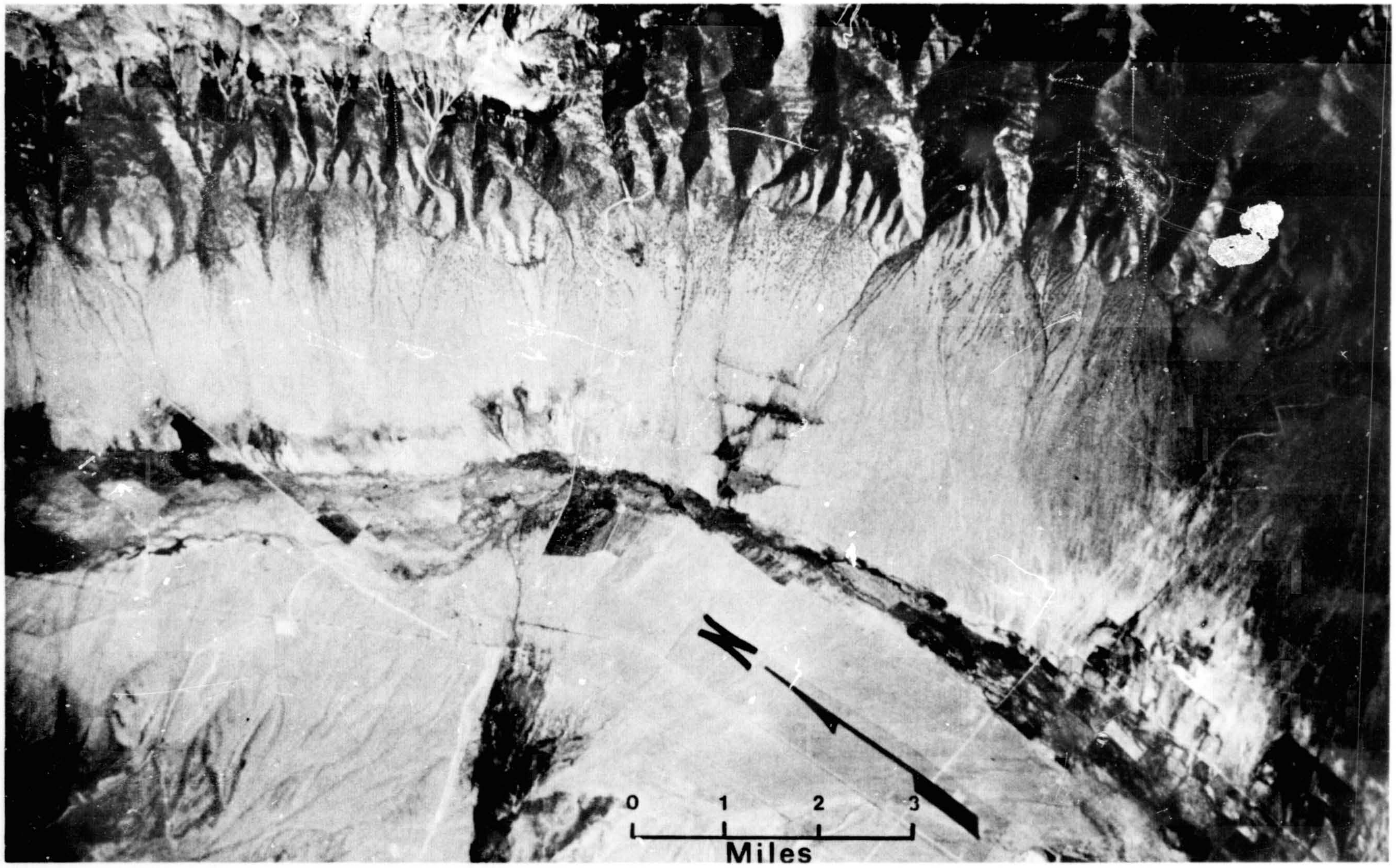
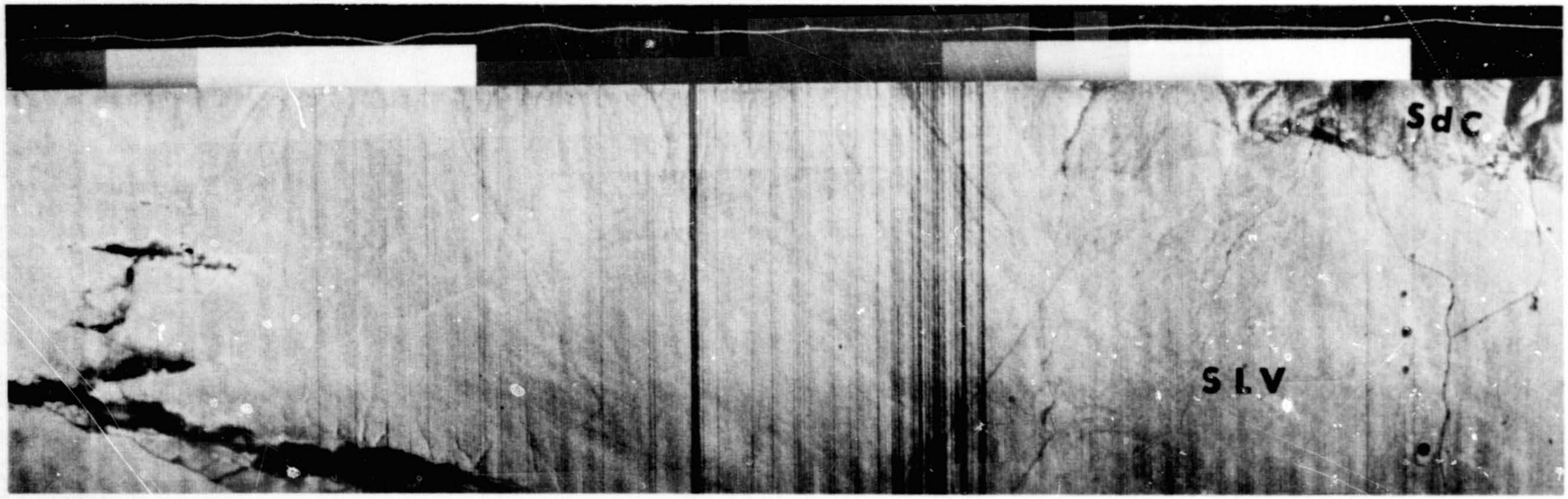


Figure 5.- Reproduction of color infrared photo over Sangre de Cristo Mtns. and San Luis Valley. SO-117 film with 500 nm filter.

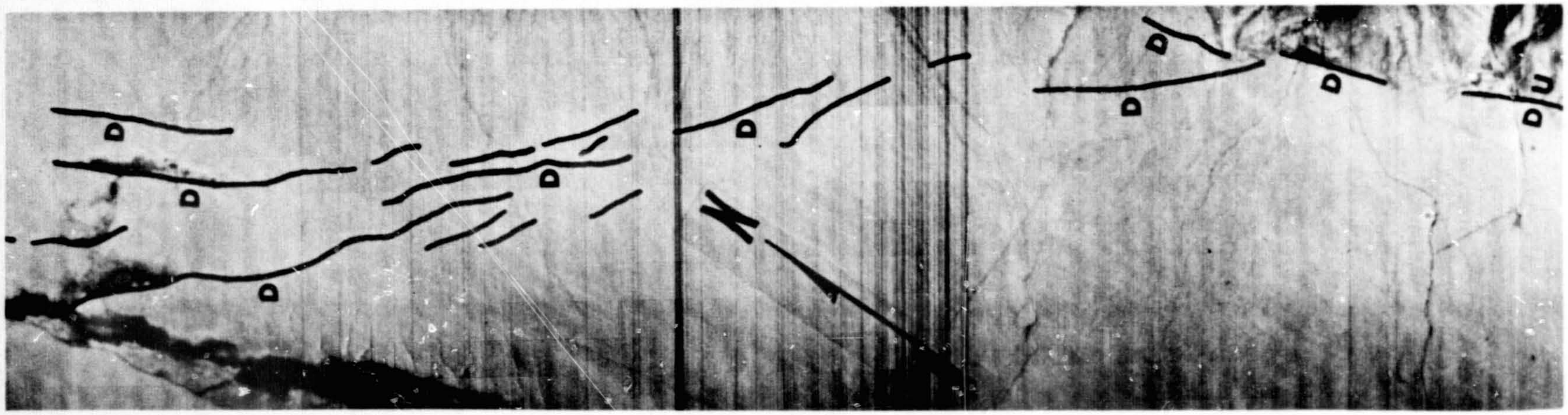
Although fault control along the base of the range is obvious across the photo, indications of fairly recent movement along the fault can be seen only in the northern part. To the immediate south of the photo, similar indications of recent displacement are also seen, but the southern half of Figure 5 lacks these features. In an attempt to locate evidence of recent faulting in this anomalous area, thermal IR scanner imagery was flown by the NASA P3A on Mission 105. Interpretation of the IR imagery also failed to detect recent faulting along the base of the range in this area, but the imagery did reveal a series of en echelon fault scarplets trending away from the mountain front (Fig. 6). Clearly then, recent stress release has occurred all along the range, but in this one area the faulting trended away from the range rather than along the base. These faults displace alluvial fans of probable late Wisconsin age, and as such are probably less than 10,000 years old. The demonstration of this style of faulting here is significant, in that it lends credence to the growing argument that the modern San Luis Valley is tectonically part of the Basin and Range province, rather than the typical Laramide Rocky Mountains.

Figure 7 is low sun-angle photography (LSAP) along the Front Range of Colorado, flown at optimum time to enhance subtle topographic variations. Geologic structure is enhanced where structure is the dominant control on topography, as is the case with these hogbacks (in areas of non-structural control of topography, such as the upper part of Fig. 7, this photography is useful for geomorphic studies). The LSAP shown in Figure 8 portrays some large faults that were not previously known, even though this area had already been mapped by conventional techniques, and permits the extension of faults previously mapped. Black and white IR film (Type 2424) was used with a Wratten 25 filter for this photography, because (1) the 600-900 nm bandpass allows better "penetration" of early morning haze, and (2) the topography is better enhanced by the strong black shadow areas that result from the lack of sensitivity to short wavelength light.

In an attempt to evaluate more quantitatively the benefit of remote sensing for obtaining geologic structural information, two small studies were conducted. In the first, interpretations of conventional aerial photos were compared with interpretations of NASA data from Mission 105 (Fig. 9 shows each of the resulting maps). The dramatic increase in structural detail is obvious, but it should be pointed out



(a) RS-14 imagery, 8-14 μm, flown 2 Oct 69 at 1308 MDT. Dark features at left appear in center of photo, Fig. 5. SdC, Sangre de Cristo Mtns.; SLV, San Luis Valley.

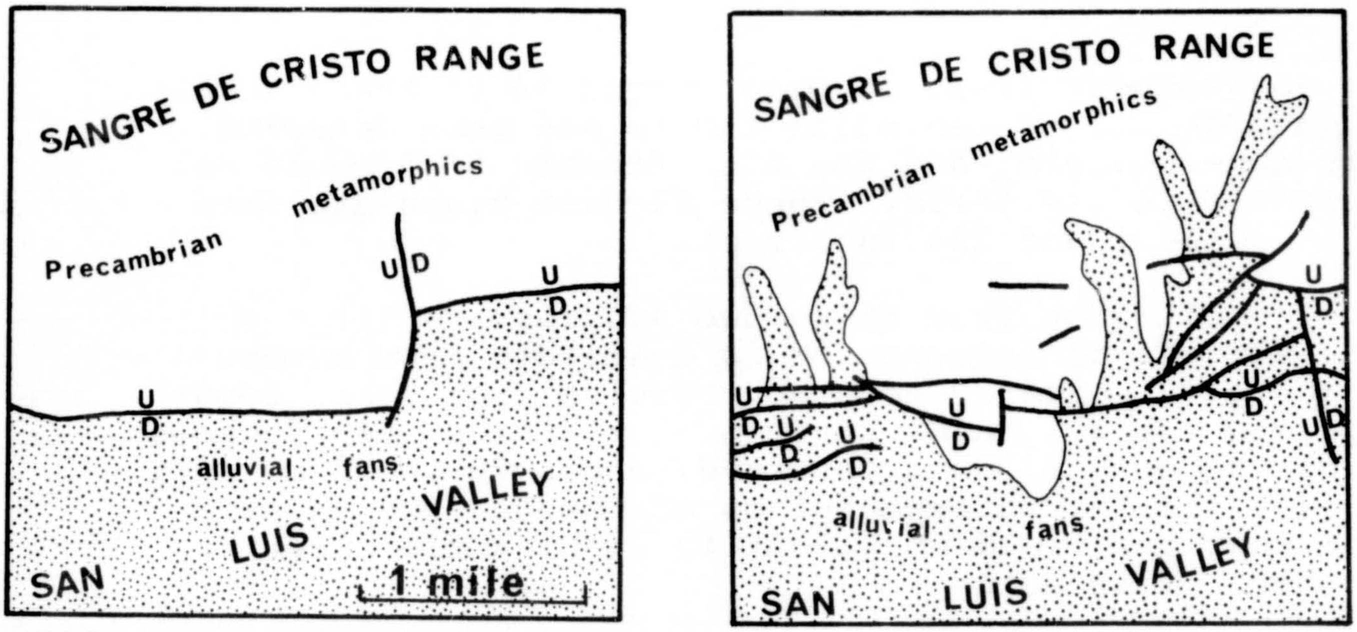


(b) Imagery same as above, with fault annotations (D on downthrown side).

Figure 6.- Recent faults on daytime thermal imagery, Mission 105.

Figure 7.- Low sun-angle photo along Front Range at Morrison, Colorado. Type 2424 film with W25 filter. Sun angle 12°.

Figure 8.- Low sun-angle photograph near Salida, Colo. Type 2424 film with W25 filter. Sun angle 20°. (pЄ, Precambrian; LP, lower Paleozoic sedimentary rocks; ℙP, Permo-Penn sedimentary rocks; Tdu, Dry Union Fm; Qf, fan.)



A. Structural interpretation from Forest Service B/W photos, 1954. (1 : 20,000)

B. Structural interpretation from MX 105 color photos (1 : 16,000).

Figure 9.- Comparison of photo-geologic maps from different types of photos.

that not only is more detail available (16 faults vs. 2 faults), but the information is more accurate, since the original interpretation was later proved erroneous. In this and nearby areas, interpretation of NASA photos delineated 26 faults. Subsequent field checking showed 8 of these to be definite faults (all of the major ones), 13 to be geologic discontinuities of some sort (not determinable in the field--either faults or fractures), and 5 were non-geologic phenomena (fencelines, trails, etc.). Thus, roughly 80% of the photo lineaments proved to have geologic significance and 20% were erroneous.

In a somewhat similar study in the Bonanza Mining District, Mission 105 data were interpreted for structural information in a complex volcanic area. These data included color and color IR photography and RS-14 thermal infrared imagery. The resulting interpretation map contained 63 faults. Subsequent field mapping proved 44 of these to be faults (again, all of the major faults had been detected), 14 to be non-geologic, and the significance of 5 could not be determined in the field. These figures translate into about 75% correct and 25% incorrect.

The conclusions from these two studies are (1) new geologic structural information is available from remote sensing data (2) greater accuracy results from using remote sensing data (3) all major structural features were detected, (4) of all structural data obtained, about 75% were correctly identified, and (5) interpretation of remote sensing data will not supplant field work, but it enables field work to be done more efficiently.

ROCK DISCRIMINATION

The ability to discriminate different rock types on remote sensor photography and imagery has so far proved to be one of our most difficult tasks, yet one which is patently fundamental to any geologic application. The obvious choice of sensors for this task, high quality color photography, has, of course, yielded the best results to date, and most likely will continue to do so. There is no need to burden the reader with yet another example of color vs. black and white photography, since the advantages of the former have been amply demonstrated. That is not to say, however, that color photography is the best tool available in all cases, and we are pursuing other techniques as well.

Although multiband photography has been used and interpreted in our work for some time now, it has only been in the past year that research has been directed toward fundamental rock reflectance studies and machine-assisted data interpretation. Geologists from CSM and atmospheric scientists from MMC have been working together in the field in an attempt to overcome problems of surface irradiance fluctuations due to atmospheric variables, and thus to obtain basic reflectance spectra of rocks on the outcrop. Figure 10 shows representative spectra, in this case for three different formations that are difficult or impossible to discriminate on black and white or color photography. Quaternary gravels (Qg) normally are impossible to distinguish from Pierre Shale (Kp), and the Niobrara Formation shales (Kn) are difficult to separate from the other two. A simple, but effective, film/filter combination which records beyond 620 nm has the capability of discriminating

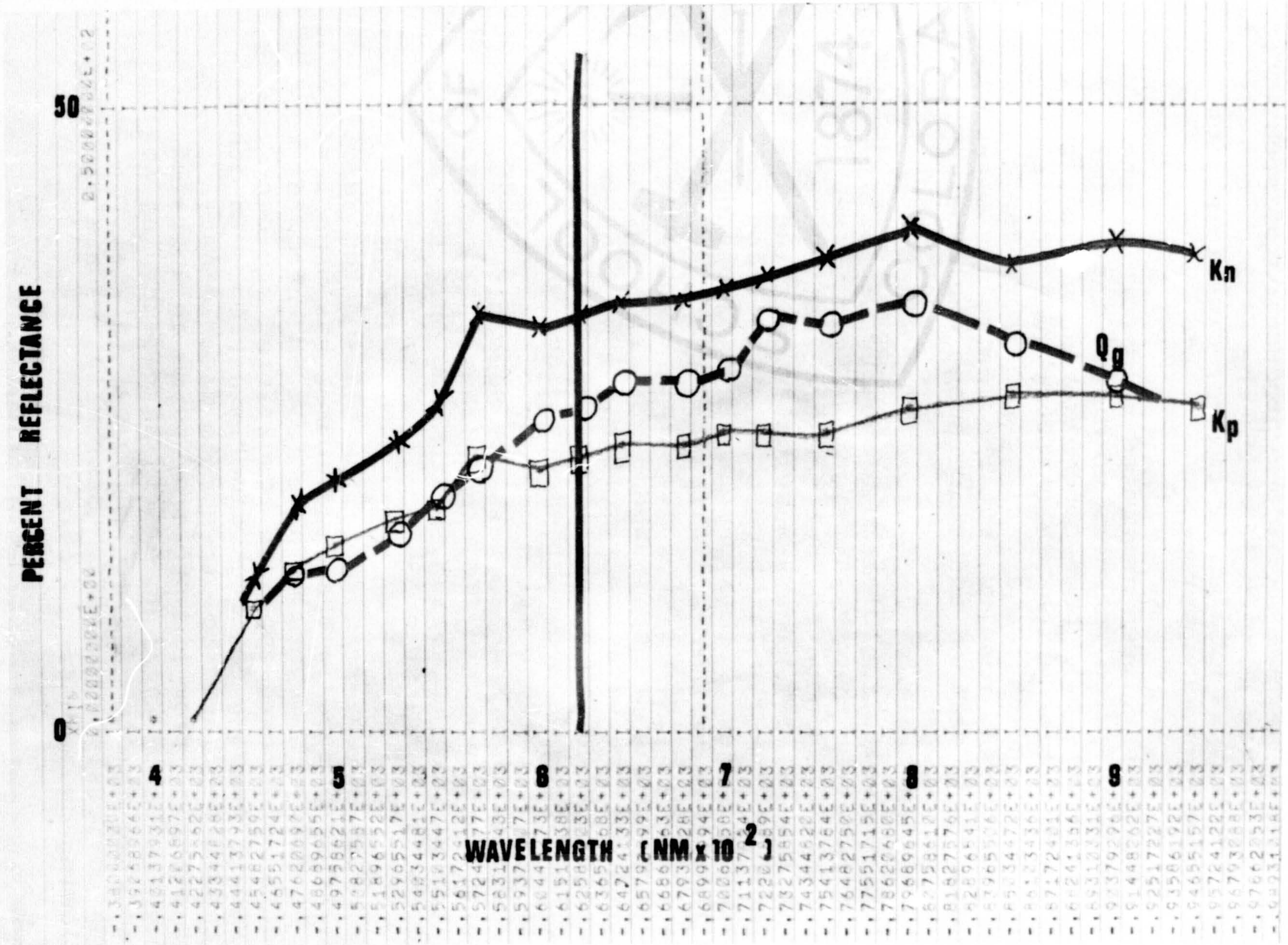


Figure 10.- Reflectance spectra of three geologic formations; Kn, Niobrara Fm. shale; Kp, Pierre Shale; Qg, Quaternary gravels.

the three rock types. Figure 11 is a reproduction of such a photo, acquired during Mission 168 with the KA62 camera and Type 2424 film with a Wratten 92 filter; discrimination of the three formations is apparent.

Similar studies have been initiated to determine the ability of thermal infrared scanners to discriminate rock types. Efforts to date have been concentrated on studying the basic rock properties which affect their radiometric temperatures. Mission 168 imagery along the Front Range has provided encouraging results, but the instrument capability remains to be defined and conclusions would be premature.

Quantitative evaluation of remote sensing capability for rock discrimination is very difficult. Conclusive studies have not been conducted, but one small study may prove informative. A test area was selected near the Bonanza Mining District for lithologic interpretation of color and color infrared photography and thermal scanner imagery. Within this test area, 78 fault-bounded areas were interpreted, and one of six lithologic designations was assigned to each of the areas. Subsequent field mapping provided ground control with the result that 62% of the areas had been assigned the proper lithology and 38% were incorrect. These figures are most encouraging, when consideration is given to the complex geology of the area; all of the rocks in question are Tertiary volcanic rocks, consisting of lava flows, ash flows and laharic breccias, and all are rather drab appearing, exhibiting only the most subtle differences in color.

To date, most of our research, like most of the remote sensing research reported in the literature, has been largely deductive. Recently, however, we have felt the need for more emphasis upon an inductive approach to defining the capability of remote sensing for rock discrimination. In other words, is it even realistic to attempt to discriminate granite, for example, from limestone by using an infrared scanner? Fundamentally then, we are in part returning to Step 1 of geologic remote sensing, where our initial residence time was obviously too brief. Basically, we are examining the following questions:

(1) What physical and chemical differences exist between different rocks?

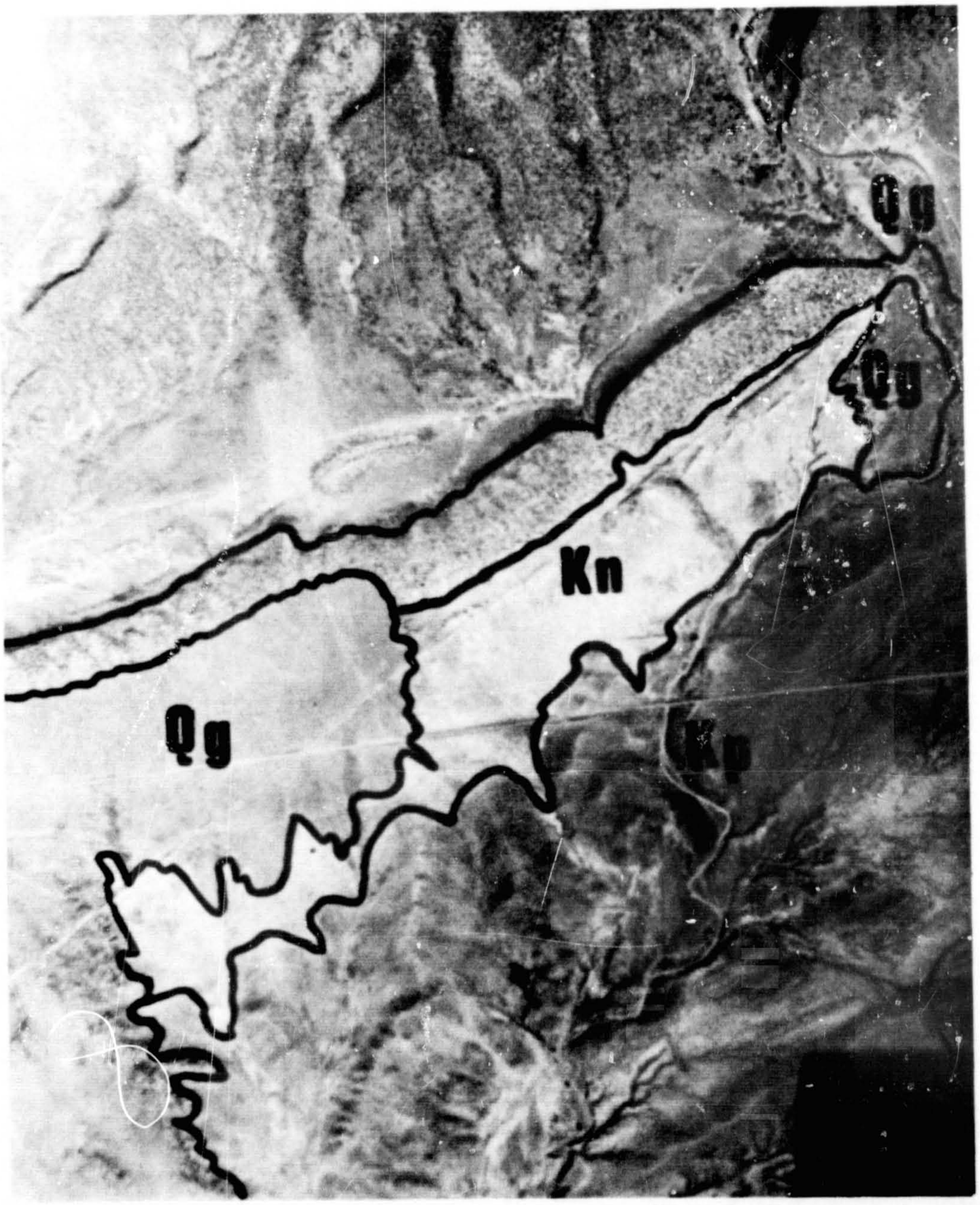


Figure 11.- One frame from KA62 multiband camera cluster. Type 2424 film with W92 filter (effective passband 620-900 nm). Kn, Niobrara Fm. shale; Kp, Pierre Shale; Qg, Quaternary gravels. Compare with Fig. 10.

(2) Which of these properties provide sufficient contrast to distinguish the rocks?

(3) Which of these properties are capable of being remotely sensed? And then logically,

(4) How can we best use remote sensors to do the job?

Our initial approach has been to examine these questions in terms of specifics, rather than generalities. Consequently, we have defined an area of study (test site, if you will) along the Front Range for this purpose, an area which includes at least 18 different geologic formations. The following procedure evolved:

A. List basic properties: All rock properties were listed. Any basic rock parameter which could be described or measured was included in the list, regardless of any other consideration. 31 parameters were listed.

B. Formation/Property Matrix: A matrix was formed in which all of the parameters from A could be listed for each of the 18 formations. Each of the spaces in this 18 x 31 matrix were then filled in (where possible) with qualitative descriptors (Table 1 is only a portion of this matrix).

Table 1

ROCK PROPERTY - FORMATION MATRIX

Formation / Property	MORRISON FORMATION	DAKOTA SANDSTONE	FT. HAYS LIMESTONE
LITHOLOGY	Shale	Qtz. ss	Limestone
GRAIN SIZE	v. fine	med	v. fine
ALBEDO	low	mod	high
COLOR	green	tan	tan
DENSITY	low	mod	high

C. Select promising parameters: Examination of the matrix focused attention upon those parameters which qualitatively showed promise of having the most contrast between adjacent formations.

D. Quantification: Attempts were made to quantify those parameters selected in C. Emphasis was placed upon methods easy to employ in the field without specialized equipment; for example, color measurements were made using GSA Rock Color Charts, and "albedo" (visible reflectance) was measured with common light meters and standard reflectance cards. An example of the resulting quantitative matrix is included in Table 2.

Table 2

ROCK PROPERTY - FORMATION MATRIX			
FORMATION PROPERTY	MORRISON FORMATION	DAKOTA SANDSTONE	FT. HAYS LIMESTONE
GRAIN SIZE (ϕ)	5	2	5
ALBEDO	30%	43%	59%
COLOR	5G 6/1	10YR 7/6	10YR 8/2
TEMP, °C 2200 HRS	-6.1	-3.2	+1.4

E. Select useful parameters: Based upon the quantitative values determined in D, the parameters found consistently most useful for discrimination were defined. For the formations in the area of study, the four most useful parameters are listed in Table 3.

Table 3

MOST USEFUL GEOLOGIC CHARACTERISTICS
• 31 PARAMETERS INVESTIGATED • 10 PARAMETERS PROBABLY USEFUL • 4 PARAMETERS MOST USEFUL 1. TOPOGRAPHIC LANDFORM 2. COLOR 3. ALBEDO 4. SURFACE TEMPERATURE

F. Define contrasts required: An attempt was made to define those contrasts between parameters which are capable of being remotely sensed. The approach here was empirical--that is, rather than simply checking manufacturers' instrument specifications (which generally apply to laboratory, or at least optimum conditions), studies were conducted on typical NASA aircraft-acquired data to estimate what contrasts have actually been detected. Some of these estimates are listed in Table 4.

Table 4

EMPIRICAL DETERMINATION OF SENSOR DISCRIMINATION CAPABILITY	
PAN FILM	15-20% albedo contrast
COLOR FILM	Hue - 2.0 Value - 1.2 Chroma - 0.8
THERMAL SCANNER	~1°C

G. *Select remote sensor(s)*: The next logical step then was to cross-correlate the matrices of parameter contrast and sensor capability in order to select the optimum remote sensor(s) which offered the greatest probability of success in discriminating the rocks.

Six different investigators followed the above procedures, each one working independently with different geologic formations within the test site. Their conclusions are shown in Table 5. It should be stressed that these recommendations apply to *these* specific formations in *this* specific test site. There is ample bias in this initial study to preclude extrapolation into other areas; nonetheless, the results are informative.

Table 5

RECOMMENDED SENSORS

Investigator	Best Single Sensor			2 Sensor Package
	1	2	3	
D. Orr	C	CIR	B/W	C + θIR
D. Knepper	C	CIR	B/W	C + CIR
G. Raines	C	CIR	θIR	C + CIR
L. Jefferis	C	CIR	θIR	C + θIR
D. Wychgram	CIR	C	MB	CIR+θIR
D. Bruns	CIR	θIR	B/W	CIR+θIR
CONSENSUS	C	CIR	B/W	C + θIR

C=color photography, CIR=color infrared photography, B/W=black and white photography, MB=multiband photography, θIR= thermal infrared imagery.