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GEOLOGIC AND MINERAL AND WATER RESOURCES INVESTIGATIONS  
IN WESTERN COLORADO, USING SKYLAB EREP DATA

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# REMOTE SENSING PROJECTS

DEPARTMENT OF GEOLOGY

COLORADO SCHOOL OF MINES ♦ GOLDEN, COLORADO

GEOLOGIC AND MINERAL AND WATER RESOURCES INVESTIGATIONS  
IN WESTERN COLORADO, USING SKYLAB EREP DATA

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## CONTENTS

	Page
Introduction . . . . .	1
Significant Results. . . . .	2
Data Quality . . . . .	3
Data Handling. . . . .	9
Geologic Structures. . . . .	18
Regional Geologic Mapping. . . . .	28
Detailed Geologic Mapping. . . . .	38
Mineral Exploration. . . . .	44
Volcano-Tectonic-Metallogenic Studies. . . . .	53

## INTRODUCTION

The primary objective of the CSM Skylab Program is to analyze EREP data for geologic information. To this end, the research has been subdivided into the following tasks;

- Task I. The PI shall assist NASA/MSC in mission planning activities related to the proposed investigation.
- Task II. The investigator will screen all EREP data obtained over Colorado and will select frames for detailed study.
- Task III. The investigator will prepare photogeologic maps using selected S-190 photographs, and will analyze them to determine what geologic information may be contained in them.
- Task IV. The geological interpretations obtained in Task 3 will be compared to interpretations obtained from S-192 imagery, and to interpretations made from ERTS-I imagery.
- Task V. The geological interpretations will be verified by means of interpretation of aerial photographs, published geological reports, and field observations.
- Task VI. The investigator will prepare recommendations for the optimum type, scale, and resolution of imagery to be used for studies of regional geology and exploration for mineral deposits and water resources.

## SIGNIFICANT RESULTS

Discovery of three major north-trending, throughgoing faults in the Front Range, previously mapped only as isolated segments, demonstrates the utility of space photography and may lead to reinterpretation of the Front Range tectonic style.

Faulting and alteration appear to be the most useful indicators of mineralization in central Colorado. These phenomena appear on Skylab photography as tonal lineaments and color anomalies.

Twenty - three lineaments have been mapped in the San Juan Mountains, the longest of which is 156 km long. Twelve lineaments intersect or are tangent to calderas. Intrusive domes are aligned along lineaments, but calderas appear to occur at the intersections of major lineaments.

Lineaments can be recognized on some EREP passes but not on other passes over the same area. The difference is attributed to solar elevation effects.

Bedding attitudes can be photogeologically estimated down to surprizingly low dips, on the order of 1-2°, and attitudes can be subdivided easily into quantitative groups.

The primary application of Skylab photography to geologic mapping in montane areas is clearly limited to regional mapping at scales smaller than 1:24,000.

## DATA QUALITY

### S190-A

There are six bands of S190-A photography: the green band covers 490-600 nm, the red band covers 600-700 nm, and two photo-infrared bands cover from 700-830 nm and >790 nm. There is also a color band and a color infrared (CIR) band.

Duplicate 70 mm positive transparencies were studied in stereo using the Bausch and Lomb zoom stereoscope at magnifications from three to fourteen power. At 3X magnification, all the photos are sharp and properly exposed. Reproduction quality is generally very good. This is also true at 14X except that the two photo-infrared bands are grainy and lack good spatial resolution.

The photo-infrared bands are best for outlining bodies of water or large streams. They also separate forest/consolidated rock areas from grassland/alluvium areas, and snow-covered from snow-free areas. CIR gives excellent detail in distinguishing verdant from water-stressed fields, fields from grasslands, grasslands and fields from forested areas, vegetation-covered from non-vegetated rock, rock from soil/alluvium, and rock of different colors. It does not, however, separate snow from cloud from light-colored barren rock. Bodies of water are

easily distinguished as black when relatively deep (e.g. - Dillon Reservoir), or blue when relatively shallow (e.g. - Cherry Creek Reservoir), and mottled when there is suspended sediment (e.g. - Elevenmile Reservoir).

The color band discriminates the same types of features as the CIR, but it is very difficult to distinguish types of growing vegetation. The color photos are best for distinguishing unvegetated rock of different colors and they are the only photos that show the subtle color changes between cloud/snow-covered and light-colored rocks.

The red band distinguishes snow/cloud from snow-free/cloud-free areas, field patterns, cultivated from non-cultivated areas, and forests/consolidated rock from grassland/alluvial material, although detail is lacking in vegetation-covered areas. The green band is good for discriminating snow and clouds from background. It poorly discriminates field patterns, vegetated from non-vegetated areas, and rock types, possibly due to poor processing, but more probably, to the extensive vegetative cover. (The green band was also studied outside of the primary interest area, with different results. In the Moab Quadrangle, southeast Utah (SL 2, S190-A, Track 34, 5 June 1973), the green band has good tonal contrast, making it superior to the two photo-IR bands for lithologic discrimination. This may be due to a general lack of vegetation in the area.)

Structure is most easily seen on CIR, color, and red bands.

On S190-A photographs at fourteen power buildings in towns (by a speckled appearance), two-lane roads (e.g. - West 44th Ave. in Wheat Ridge, Interstate 24 through South Park), and airport runways (e.g. - at Leadville, 4800 feet long, 175 feet wide) can be discriminated and objects as small as Golden Reservoir (approximately 800 feet diameter) and Interstate 70 (approximately 200 feet wide) can be identified.

#### S190-B

Positive transparencies 4 1/2-inch square were studied both in the monoscopic and stereoscopic modes (depending upon endlap), using the Bausch and Lomb zoom stereoscope at magnifications from three to fourteen power. Over the central Colorado survey area only color photography without endlap is available. The S190-B photos are easily viewed at three to fourteen magnifications, have sharp contrast, and are properly exposed. Reproduction quality is excellent.

The high-resolution color photography gives excellent discrimination of fields from grasslands, grasslands and fields from forested areas, vegetation-covered from non-vegetated rock, rock from soil/alluvium, rocks of different colors, bedded from non-bedded rocks, fractured from non-fractured rock, snow/cloud cover from light-colored rock, and bodies of water. Large throughgoing (regional or "geotectonic") structures are best observed at three power

magnification, while fairly small structures (e.g. - fracture systems in granite) are easily seen at fourteen power.

On S190-B photography at fourteen power, clusters of buildings in towns, large isolated buildings (e.g. - Carlton Gold Mill at Cripple Creek has an aluminum roof and is approximately 300x600 feet), and unimproved roads (e.g. - power plant road east of Leadville, approximately 30 feet wide including shoulders) can be discriminated and tailings piles and color anomalies approximately one mile in diameter (tailings at Alma or Cripple Creek; weathered pyrite at the Sweet Home Mine, Buckskin Gulch near Alma), islands as small as 300 feet diameter in lakes (e.g. - Electra Lake north of Durango and Elevenmile Reservoir), and linear features such as the paved portion of the runway at the Leadville airport (72 feet wide, 4800 feet long) or improved roads (e.g. - Interstate 285 between South Park and Morrison, approximately 50 feet wide including shoulders) can be identified.

S192

Positive transparency "screening film" (1-inch-wide strips) of Channels 2 (460-510 nm), 7 (780-880 nm), and 11 (1.55-1.75  $\mu$ m) was studied in the monoscopic mode using the Bausch and Lomb stereoscope from three to fourteen power. When properly exposed and viewed at small magnifications, the film has very good contrast. The film

becomes grainy - that is, the spatial resolution is degraded - at approximately five to six magnifications. Channel 11 appears to have better contrast than Channel 7, and both appear better than Channel 2.

Channel 11 distinguishes clouds (white) from old snow (black), it separates rivers and bodies of water (black) from the background, and is very good for distinguishing structures and lithologies in lightly vegetated areas (area around La Sal Mountains). Channels 7 and 2 show the same features in correspondingly poorer contrast, except that old snow appears white, and water appears gray.

At 3X magnification lithologic contacts between the Jurassic, Triassic, and Upper Permian units in eastern Utah can be discriminated and features such as the goose-necks where the Green River joins the Colorado (as small as one to three miles across) can be identified.

#### Evaluation of Data Received

a. Skylab 2 S190-A photography taken June, 1973, generally has minor cloud cover (less than 20%), but has snow at all high elevations (over 11,000 feet). In most cases the snow degrades the quality of the photography, although some structural features that are expressed topographically are enhanced by the snow cover (e.g. - Mosquito-London-Weston Fault complex).

b. Skylab 2 S192 multispectral imagery, taken in June 1973, has almost no clouds, and snow only at high elevations (over 11,000 feet). The snow degrades the quality of the imagery.

c. Skylab 3 S190-A photography taken in August 1973 has very little snow, but cloud cover (generally greater than 60%) degrades the information content.

d. Skylab 3 S190-B photography taken in August 1973, has the same characteristics as the Skylab 3 S190-A photography.

## DATA HANDLING

### Non-enhanced Photography and Imagery

Photographic and imagery products received from NASA are generally interpreted as received, without further data processing other than magnification and stereoscopic viewing.

Because Skylab images contain more geologic information than can be interpreted at the original film scales, direct interpretation is not efficient, and magnification is necessary. The most effective method of interpretation is through high quality optical systems, rather than photographically enlarging the originals and using enlarged prints or transparencies; this avoids another generation or two of film degradation. Skylab S190A photographs have an original scale of about 1:2,850,000; 12X seems to be about the maximum magnification, to a scale of about 1:240,000. Skylab S190B photos will take similar magnification, from an original scale of 1:950,000 to about 1:80,000. The Richards MIM light tables, with a Bausch & Lomb 240R zoom stereoscope, are ideally suited to magnified stereoscopic and monoscopic photointerpretation.

As Skylab films contain more geologic information than can be interpreted at original scales, they likewise

contain more information than can be graphically represented at original scales. Therefore, photographic enlargements are also required to map the interpreted information, either directly onto the enlargements or onto clear overlays. A good method entails interpretation of low-generation contact positive transparencies under stereo (where available) magnification, with interpretive results transferred to clear overlays on enlarged transparencies or prints. The annotated images can then be transferred to topographic maps with the Bausch & Lomb zoom transfer scope.

At whatever enlargement, or under whatever magnification, the quality of film transparencies is superior to that of paper prints. However, in the ultimate interpretation step - field checking - transparencies are difficult to use, and prints are far handier (and cheaper). A good compromise is to annotate onto clear overlays, which can then be put onto prints for field use.

#### Data Enhancement

When developing prints of the S190-A and S190-B that will be used for structural analysis or slip masking, high contrast copies are easiest to work with. High contrast is obtained by using a high contrast film or by increasing the developing time. High contrast enhances linear features, which are usually expressed (due to topography) as dark vs. light areas.

## Slip Masking

Positive-negative slip masking (Lee, 1972, 1973) can enhance linear features. Features are enhanced that trend from approximately 20-90° from the slip direction. Comparison of photolines from a slip positive-negative mask with an original positive shows that some significant linears may be found in this manner, but that some are overlooked because of the blurring that accompanies slipping.

## Direct Overlay Masking

Direct overlay positive-negative masking was undertaken using 9x9 inch positive and negative transparencies of Frame 17, Track 48, Skylab 2 S190-A taken in June, 1973. Transparencies were available from Bands 15 (700-830 nm), 08 (>790 nm), 06 (600-700 nm), and 10 (490-600 nm). Each positive was masked with the negatives from the three other bands, and each negative was masked with positives of the other bands, eight combinations in all. These were observed, and notes were taken as to which combinations were best for isolating certain features. Features most likely to be isolated are clouds, snow-covered terrain, bodies of water, verdent vegetation (ie. growing fields, streambed vegetation), grassland/alluvium, and forests/consolidated rock. Subdivision of lithologies depends mainly on structure and vegetation, and vegetation is variable from one locality to another (other factors, such as moisture, slope,

elevation, etc., affect vegetation more than rock type). Structure is seen as a textural, rather than tonal variation, and direct overlay masking damps textural features. Therefore lithologic discrimination is difficult.

Good contrast of features other than lithology is seen by masking the positive of Band 08 with the negative of Band 15. Topography is eliminated, snow and clouds are light gray, grasslands and alluvium are medium gray, forests and consolidated rock are dark gray, and water bodies are black.

Good contrast of features is also seen when masking the positive of Band 08 with the negative of Band 06. Snow, clouds, and water bodies are black, verdent vegetation is nearly white, grasslands/alluvium are medium gray, while forests/consolidated rock are dark gray (the negative of the red band gives the same information, except water bodies are white).

It appears that direct overlay positive-negative masking provides little unique geologic information.

#### Color-additive Viewing

Color-additive viewing (CAV) was carried out using the International Imaging System (I<sup>2</sup>S) Mini Addcol and Frames 106 and 107 from Track 48, Skylab 3 S190-A taken August, 1973. Film chips used were the 70 mm positive and negative transparencies of the two photo-infrared bands, the red and green bands, and the positives of the color and CIR bands.

Three combinations were investigated for enhancing color anomalies. To enhance red rock, possibly associated with mineralization, set the color positive on clear light at an intensity of 9 (on scale of 0 to 9, with 9 maximum), the positive of the CIR band on blue at 7, and the negative of the red band on clear at 9. The second combination uses the positive of the color band on clear at 9, the negative of the red band on green at 6, the negative of the photo-infrared on blue at 9, and the positive of the red band on red at 5. This makes all rock/soil varying shades of red. The third alternative is true color.

Another type of color anomaly is the light-colored rock in an area of darker rocks (e.g. - Tertiary intrusions into Permian-Pennsylvanian sediments along the crest of the Mosquito Range in the southern Leadville mining district). The first and third techniques mentioned above do a fair job of isolating light-colored rocks.

The third type of color anomaly is the dark-colored rock in a generally light-rock area (e.g. - Miocene breccia and phonolites surrounded by pink Precambrian granites in the Cripple Creek area). It is very difficult to isolate this type of anomaly because most vegetation cover, as well as shadows, are also dark on the photography. Preliminary work shows the color band is best for finding these anomalies.

## Density Slicing

Density slicing of positive or negative transparencies from any band may be used effectively to isolate light or dark color anomalies (anomalous red areas are usually a medium gray on a black/white density slice, and are not anomalous). Slices may be made using high contrast film and varying the f-stop, exposure, or developing time during copying.

Diazo color-additive density slicing was tried on Skylab 3 S190-B photos. The process involves color coding of gray levels on the original. Negatives were made from the positive of the red band. Density slices were made using high contrast film and varying the f-stops on the enlarger, with exposure and developing time constant. f/5.6 gave the darkest and f/22 gave the lightest negative density slice. The diazo film produces color only in the dense (dark) areas of the transparency (in this case, the negative). Using only negatives, a four-colored image may be produced (Fig. 1a).

Black and white negatives were made from frames 38 and 39 (color transparencies), and then contact positives were made (on normal contrast film) from the darkest negative. The density slice color code scheme may be seen in Figure 1b. Using both positives and negatives, a six-colored density image may be produced. Additional densities may be sliced by varying the exposure and developing times.

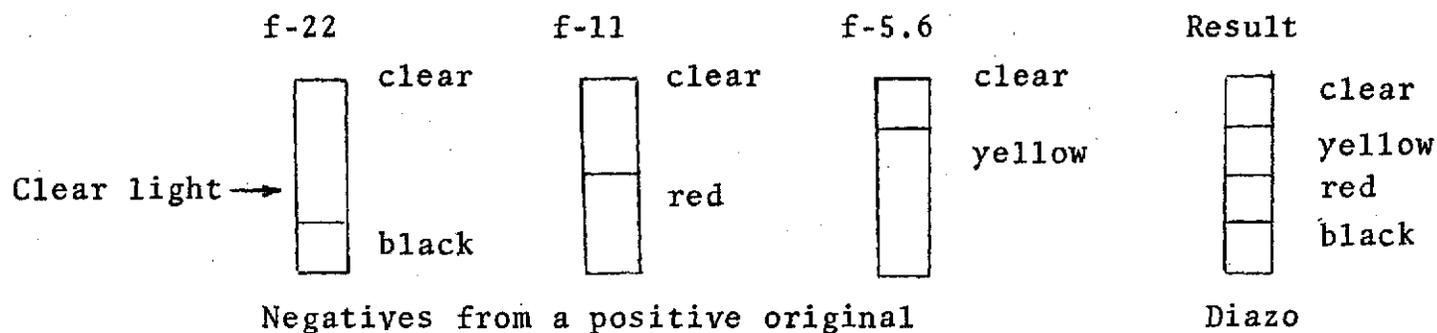


Figure 1a. Schematic of a diazo four-color density slice image produced from negative transparencies.

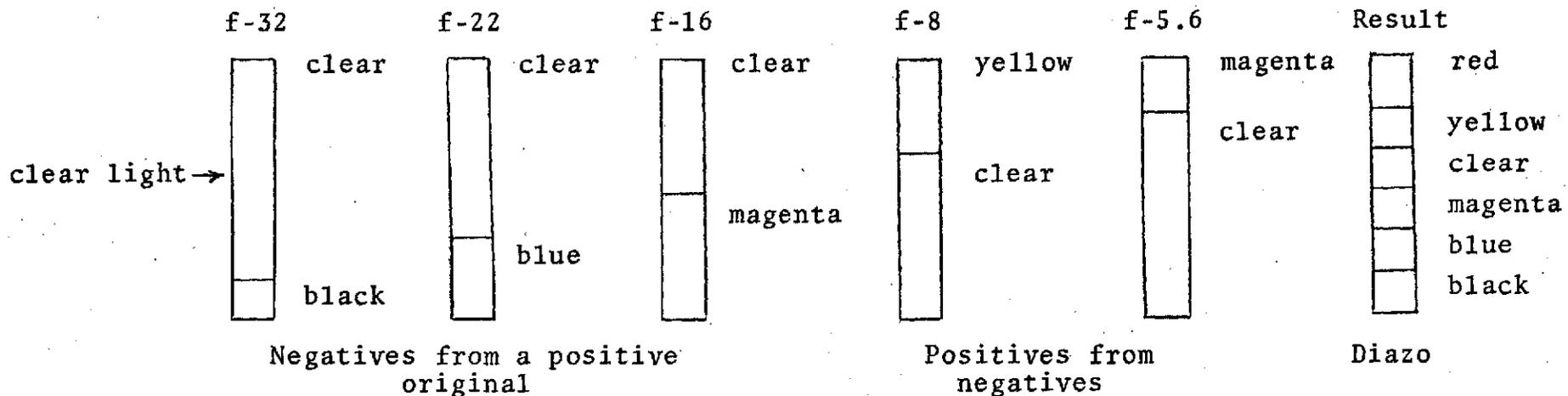


Figure 1b. Schematic of a diazo six-color density slice image produced from negative and positive transparencies.

Color coding of density slices gives inconsistent results due to the change in radiance of an object corresponding to changes in the geometric relationship (aspect angle) between the camera, object, and source of illumination. For example, a lake (smooth surface) will appear light when between the camera and the sun, and dark when the camera is between the sun and the lake (Figure 2). Because of this relationship,

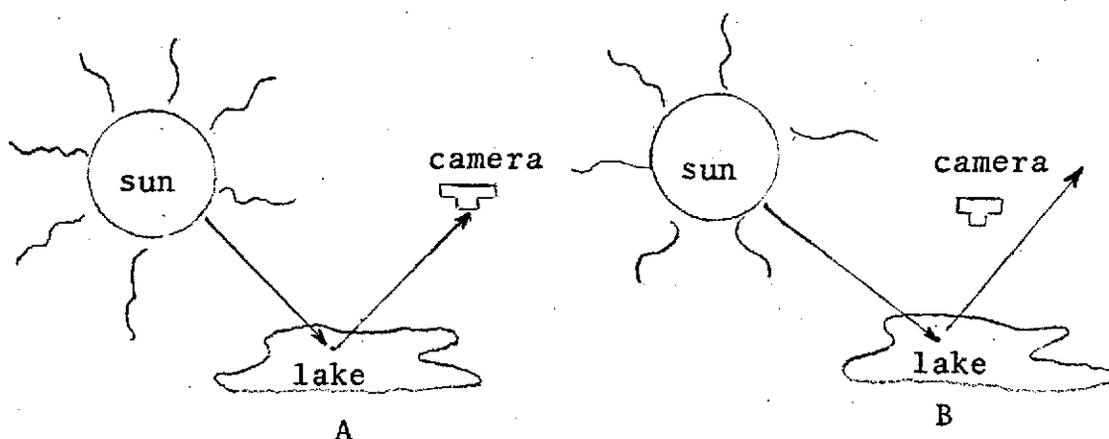


Figure 2. Change in reflectance of a lake corresponding to a change in the geometric relationship between camera, object, and illumination source. In A the lake appears bright, while in B the lake appears dark.

bodies of water were sliced at three densities. The same principle, although opposite in sense, can be extrapolated to rocks, soils, and vegetation (rough surfaces). Red sandstones of the Maroon Formation near Antero Reservoir were on one slice, while outcrops of the same red sandstone were on another slice near Ruedi Reservoir. It is also probable that one density slice contains many different objects of interest. For example, the Maroon Formation near Antero

Reservoir was in the same slice as the water in Elevenmile Reservoir and most of the grassland in South Park.

There is, however, a tendency for vegetation to be the same density from one region to another, and the diazo process may be good for lithologic discrimination in a fairly uniform geologic area. For example, all the outcrops of volcanics in southern South Park are on the same slice (this may be a result of uniform vegetation cover). The diazo process is capable of enhancing the contrast between light and dark areas on a photo or image, and thus may make topographically expressed linears easier to see.

## GEOLOGIC STRUCTURES

This study covers (1) the ability to recognize geologic faults and folds, (2) the relationship of long linears to the regional fracture system, and (3) the relationship of the trends in the set of all linears to the rock joint systems.

### Central Colorado Test Site

The Central Colorado Test Site lies at the intersection of Skylab Tracks 34 and 48. Specific areas covered are the Rampart Range, southern Front Range, Canon City Embayment, Royal Gorge arch, and eastern South Park. The geologic provinces consist of the Pikes Peak batholith, metamorphic rocks south of the batholith, and the folded and faulted Paleozoic and Mesozoic sedimentary rocks around the margin of the southern Front Range and Canon City Embayment. Royal Gorge arch is a metamorphic terrain, including the Blue Ridge area, flanked by folded Paleozoic and Mesozoic strata. Eastern South Park consists of folded Mesozoic and Tertiary strata and a metamorphic terrain.

### Data

Photography of Skylab 2 (June 1973) and Skylab 3 (August 1973) was available for Track 48 only. Photos from S190A black-and-white bands, color, and color infrared were evaluated.

Several published geologic maps are available for ground truth acquisition. In addition, there are many dissertations and theses of the area. These sources are supplemented with abundant private field notes.

Aircraft photography flown in support of Skylab, ERTS, and the Bonanza Project was also used. Mission 261 is low-sun angle, black-and-white IR, RC-8 photography, flown as an underflight to Skylab 4. Missions 205 and 211 are color (RC-8) and color IR (RC-8 and Zeiss). On the 9 in. by 9 in. format, this photography is at a scale of 1:100,000.

Relief models of the area (1:250,000) were painted white and photographed at various sun azimuths at low sun elevation in order to enhance dominant topographic trends. This information is low resolution, but because only topographic relief is conveyed, the information is distinct and free of other confusing elements.

It is clear from these studies that the multi-scale approach yields the most geologic information. Each scale of photography has its distinct features and provides unique information for the whole, whether for evaluation of small geologic features or for interpretation of large features.

#### Data Recommendations

Because of the extreme variability of cloud cover, seasonal changes in vegetation, the sun's declination, Skylab data are degraded because of the few overflights of

this area. In future missions of the Skylab-type, photographic overflights should be scheduled to take the best advantage of these variations.

In this area, cloudiness over mountainous areas is often a function of the prevailing westerlies and high elevations. In our experience, such local instabilities are decreased or non-existent after the passage of a cold front in all seasons. Local and regional cloudiness can be selectively avoided by observing the regional weather patterns.

For maximum shadow enhancement of structural features, times of optimum sun elevation and azimuth should be used (Sawatzky and Lee, 1974). The effectiveness of sun attitude is demonstrated in this study. Three new north-trending linear features in the Rampart Range were discovered on SL-2 photography and not seen on SL-3 photography. This is attributed to the favorable sun attitude of SL-2, when the sun azimuth was  $92^{\circ}$  and sun elevation was  $40^{\circ}$ , whereas for SL-3 the sun azimuth was  $132^{\circ}$  and the sun elevation was  $57^{\circ}$ . The reverse was true for linears in the Royal Gorge arch, which trend N  $80^{\circ}$  E. Linears with greater relief (such as in the Dome Rock area, N  $10^{\circ}$  E) are visible on both SL-2 and SL-3 on all bands. Linears oriented  $45^{\circ}$  to the sun azimuth are recognizable on the best imagery of both missions, such as in the Blue Ridge area.

## Best Photography Characteristics

The features of Skylab photography that make it preferable to ERTS imagery are its full stereoscopic capability, higher resolution, and better color rendition. These features increase structural information that is very dependent on topographic effects, vegetation differences, soil and/or rock color contrasts. To this is added the synoptic view of orbital photography.

Of all bands, color and color infrared are best for different reasons. The enhancement of linear features depends very much on shadows. Where dark green vegetation masks the effect of shadows on color photography, shadows and vegetation are distinguishable on color IR. This is well shown on the SL-2 photography. Thus, while the unfamiliar color rendition of color IR will not supplant the more familiar true color photography, it will be useful in the interpretation of fractures.

Color is superior to color IR in the interpretation of the folds along the Southern Front Range in the Canon City Embayment. This is demonstrated on SL-3 photography. The reason lies in high spectral contrasts of three sedimentary formations involved in the folds. The Fountain Formation has a reddish-orange soil with little grass and few trees. The Dakota Group is heavily covered with dark-green Utah juniper, some pinyon pine, and Gambel oak brush. The Niobrara Formation has a light-gray to cream soil with

sparse grass and few trees. On color images the boundaries between these formations are sharp, and mapping of the folds is easiest. On color IR the spectral contrasts are low and not useful. In addition, Band 10 shows no contrast between Fountain and Dakota, but Niobrara recognition is good. Band 6 shows some distinction between Fountain and Dakota in the medium gray range, and Niobrara is light gray. Bands 8 and 15 are not useable because of very low contrasts and severe graininess. Table 1 gives an evaluation of the recognition of certain features on SL-2 and SL-3 photography.

#### New Geologic Information

The unification of one aspect of regional geology by orbital imagery is reflected in some discoveries in the Rampart Range. One strong, north-trending linear was first recognized on ERTS image 1172-17141 (January 1973). This linear was again recognized on SL-2 photography, with the addition of two less prominent linears subparallel to the first. On high-altitude photography, these linears are unmapped extensions of the Ute Pass fault and two other major faults bounding the Manitou Park outlier west of the Rampart Range as described by Harms (1959). The easternmost linear transects the Rampart Range from Manitou Park northward and passes into the Perry Park faults on the east side of the range (Harms, 1959, Plate 1). The central fault

TABLE 1 - Recognition values of lineaments in several areas of the Central Colorado Test Site as a function of Skylab mission and band for magnified stereoscopically-viewed 2 in. by 2 in. positive films.  
G - good, F - fair, P - poor, N - none, c - cloudy.

A. SL-3 S190A, frame nos. 106-108

Band	Area							Comments
	Rampart Range	Royal Gorge	Dome Rock	S. Front Range	Blue Ridge	H. South Park	Red Creek Folds	
CIR	GC	G	G	GC	G	NC	P	better than color dense positive
color	PC	G	G	GC	G	NC	G	
10	GC	G	G	GC	G	NC	F	
6	P	G	G	GC	G	NC	F	
8	P	P	G	P	P	NC	N	low contrast
15	F	P	G	P	P	NC	N	low contrast

B. SL-2 S190A, frame nos. 17-19

CIR	G	P	G	NC	G	FC	NC	very blue, crisper in detail than color
color	G	P	G	NC	G	FC	NC	
10	G	P	G	NC	G	FC	NC	
6	G	P	G	NC	G	FC	NC	
8	G	P	G	NC	P	NC	NC	
15	G	P	G	NC	P	NC	NC	

(in part, the Devil's Head fault of Boos and Boos, 1957, Figure 9) trends northward from the monoclinial axis along the east margin of Manitou Park (Harms, 1959, Plate 1) across the range into faults in the Jarre Canyon area (Hutchinson, 1960; Johnson, 1961). The westernmost fault is paralleled by many sandstone dikes and extends northward (Hutchinson, 1960, Figure 1) into the Kassler Quadrangle where it is known as the Bear Creek shear zone (Scott, 1963). These three major faults have been mapped only in isolated parts. Orbital imagery has provided a unifying synoptic view which may bring about reevaluation of the tectonic style of the Front Range.

Four parallel linears trending N 45 E in the Southern Front Range transect the Precambrian rocks and cut folded Paleozoic and Mesozoic sedimentary rocks on both flanks of the range. That these linears extend into known faults and cross the block uplift is a new discovery that will modify the future studies of the tectonic style of the area.

The Skagway linear extends from the offset between Sheep Mountain and the Milsap Canyon thrusts on the west side of the range northeastward some 15 miles into the Pikes Peak intrusive center. The Adelaide fault (Boos and Boos, 1957, Figure 11) extends from the transverse fault at Felch Creek on the west side of the range for about 15 miles into faults offsetting lower Paleozoic strata in the lower Beaver Creek area on the east side. Two shorter

linears lie in between these, one of which extends about 10 miles into the Pecks Camp mineralized area on East Beaver Creek.

The Precambrian core of the Royal Gorge arch has been mapped only with respect to lithology, and the existing map (Heinrich, 1948) shows only ENE trending metamorphic layering. Three prominent topographic linears are visible on SL-3 photography. As found in other areas, these linears extend into and transect upturned strata on both flanks of the uplift. The relationship of these linears to faults can be clearly demonstrated.

In eastern South Park is an example of the discovery of linears extending into known faults. Two major faults cut obliquely across folded Tertiary strata in the San Isabel syncline (Sawatzky, 1967). They are parallel and trend N 30 E. Two linears extend NE from the known faults and cut across the Elkhorn thrust and into the Precambrian rocks of the thrust. One interpretation is that the oblique faulting is post-thrusting.

#### Linears and Joints

Most prominent linears are related to faults, as discussed above. The origin of the ubiquitous short linears on orbital imagery has been investigated with the search for a relationship with the regional joint systems. Since the area for which there are available ground

measurements, the southern Front Range, is cloud-covered on SL-2 and SL-3 photography, ERTS imagery has been examined in anticipation of clear SL-4 photography.

The first approach was to measure the azimuths of all linears in an image, usually 350 to 400 in numbers. Trend analysis reveals several closely spaced but significant trends, which are difficult to correlate with joint trends for the region. The difficulty appears to lie in strongly localized trends probably resulting from quite variable erosional enhancement. Ground truth is available for analysis for four small areas. The analysis of the southern Front Range area has been done.

Three joint trends were determined from approximately 500 field measurements in the Phantom Canyon: a weakly-displayed N 52-62 W (WNW) trend, and two prominent trends at N 17 W - N 12 E (N-S) and N 66-76 E (ENE). Mission 261 low sun-angle photography (sun elevation =  $10^{\circ}$ , sun azimuth =  $135^{\circ}$ , scale = 1:100,000) displays three trends of ubiquitous short linears. The N 53-75 E trend contains few short linears, but includes the Skagway and Adelaide faults, and corresponds to the strong ENE joint set. Another set of linears trends approximately N 14-20 E, includes the Mountaindale fault, and falls within the strong N-S joint trend. This is a very prominent set of linears on the relief map under southwest illumination. A third linear set trends from N 16-31 W and most likely also

corresponds to the broad N-S joint trend. The major fold axes east of the range parallel this trend. This trend is prominent on the relief map under south illumination. Joint analysis has not distinguished these NNW and NNE trends that are so prominently displayed as linears on photography. A fourth linear set is weakly displayed in the range of N 68-81 W and probably corresponds to the WNW joint trend.

The short ubiquitous linears on the relief model of the southern Front Range were measured and combined for four illumination directions 45 degrees apart. The resulting trends are, N 62-63 W, N 14-22 W and N 30-50 E, which correspond well with the joint sets. The linear trends determined for the area from the ERTS image (sun elevation = 23°, sun azimuth = 150°, scale 1:1,000,000) were greater in number and less distinctive. In general, the main trends are WNW, NNE, and ENE. The broad N-S linear trend was not recognized, and the other trends were not strong. The high sun angle (23 degrees) greatly diminishes the effect of shadow enhancement of topographic linears, as few topographic slopes are greater than 23 degrees. This does not completely explain the inability of the orbital imagery to strongly reflect the regional joint systems, as the relative importance is not fully known.

## APPLICATION OF EREP DATA TO REGIONAL GEOLOGIC MAPPING

Preliminary regional geologic studies using Skylab photography have been done in some detail in the Moab, Utah area, and in lesser detail in central Colorado, especially from South Park southeast to the Wet Mountains. In general, the Colorado investigations are hindered by vegetation, local snow, and variable, but often widespread, cloud cover.

### Data Evaluation

Data evaluation has been mostly confined to the 190B color photography, where available, and the 190A color and CIR photography, with some comparisons with other 190A bands. Brief comparisons with ERTS-1 imagery have been made and will be continued in more detail. The 190B photography is superior, in those areas investigated, to any other Skylab or ERTS-1 data for general photogeologic interpretation, although much of the same information is also present in the 190A color and CIR photography. This superiority is due to the higher resolution, detectability, and recognizability aspects of the 190B photography, which allow smaller geologic elements to be better interpreted. The best 190A band for general photogeologic interpretation, in the areas investigated, is the color band, followed in

utility by the CIR. No significant geologic features were uniquely interpretable, in this preliminary investigation, from the other 190A bands to indicate greater utility than the color or CIR. The black and white infrared 190A photography is excessively grainy; the 190A CIR photography is somewhat more grainy than the color.

### Interpretation Techniques

The main interpretation technique used was stereoscopic examination, both with a Bausch and Lomb 240 zoom stereoscope-light table and with a simple mirror stereoscope on a light table. The mirror stereoscope interpretations are easier and to some extent better than those with the zoom stereoscope, especially for regional investigations where the synoptic aspect of the photography can best be utilized. The limited field of view of the zoom stereoscope hinders full utility of the synoptic aspect, although the zoom capability is good for point interpretations.

Annotations have been made on acetate overlays of 190B 2X positive transparency enlargements (scale about 1:472,000) and 190A 4X positive transparency enlargements (scale about 1:711,000). Even with the enlargements, there is insufficient room to annotate all data that can be interpreted. Other techniques being tried include rapid preliminary interpretation annotated on an overlay, followed by a more detailed interpretation and simultaneous visual transfer to an acetate

overlay of an enlarged photographic print at a scale of about 1:250,000. This is a very time-consuming process but best preserves the precise spatial arrangement of interpreted data. Transfer of data from an annotated overlay of the positive transparencies to an enlarged photographic print as above has been attempted with a Bausch and Lomb zoom transferscope but considerable detail is lost in the process. The annotation and posting process is one of the biggest problems with Skylab interpretations.

### Study Results

In the Moab area, excellent exposures allow tracing of stratigraphic contacts in considerable detail. Photo-geologic unit contacts were selected without previous reference to the established stratigraphic terminology, as if the area were completely unknown. The synoptic aspect of the photography greatly assisted in this interpretation by allowing rapid visual comparisons with contacts mapped in other parts of the area; with conventional aerial photography this process often requires going from one photograph to another or several others. Most contacts could be interpreted from 190A color photography (positive transparencies) in greater detail than could readily be annotated; even more detail is present in the 190B photography, allowing more subdivisions and continuity. Subsequent comparison with a published geologic map

(Williams, 1964) indicated that many of the contacts of the geologic map had been interpreted from the Skylab photography and that others could have been, particularly with 190B photography. Comparisons were less favorable in highly complex areas, especially with small features, and in densely vegetated areas such as the upper slopes of the La Sal Mountains.

Much of the structure of the area around Moab could be readily interpreted from 190A color photography; again, more detail is present in the 190B photography, allowing easier and, to some extent, more accurate interpretations. Bedding attitudes were estimated from the 190A color photography by standard photogeologic techniques, but, in this case, without any previous reference to published attitudes or concern with estimation of the relief exaggeration present in the stereo model. The estimated dips were arbitrarily divided into three dip groups, ranging from the most gentle to the steeper dips of the area. Subsequent comparisons with dips on the geologic map (Williams, 1964) indicated that the category of most gentle estimated dips corresponds to mapped dips of 1-6°, with an intermediate category of about 3-15°, and a steeper category of about 10-30°. Comparison of strike directions was generally quite favorable. It is anticipated that greater experience with the stereo model of the Skylab photography could lead to refinement of this technique. The 190B photography would

probably give better results, with less indecision about problem attitudes. Lee and others(1974) were able to recognize bedding attitudes as gentle as  $2^{\circ}$  dip on 190B photos. The ability to differentiate these low dips, especially on the 190A photography, was somewhat surprising and should have great significance in regional mapping and structural interpretation. These estimations were made with a simple mirror stereoscope, without additional magnification. The possible advantages or disadvantages of the Bausch and Lomb zoom stereoscope for dip estimation have not yet been investigated in detail. The initial impression was that the relief exaggeration of the Skylab photography stereo model would be too low to allow much differentiation of estimated dips. In practice, the advantageous factors of near-orthographic photography and the synoptic view greatly assist in estimation of dips by presenting a uniform view of a large area, with uniform tip or tilt distortions, if any, and by allowing rapid visual comparison of estimated dips in other parts of the area. In contrast, with conventional aerial photography, similar comparisons often require going through perhaps several individual photographs, each of which could have varying tip and tilt distortions. Of course, greater relief exaggeration can be acquired with conventional aerial camera systems, but this greater relief exaggeration can be a problem, especially in areas with considerable topographic relief. It is likely that without

good exposures of bedding surfaces of considerable areal extent, dip estimations would become more difficult and less accurate as exposures become poorer and bedding surfaces smaller.

Many faults could be interpreted on the 190A color photography as visual traces with stratigraphic or topographic offset. Other probable faults could be interpreted with more study of the photography and better familiarity with the local stratigraphy, but some complex, small, or partly concealed faults mapped in the field probably could not be interpreted from Skylab photography. For a fuller discussion of the expression of faults on Skylab photography, as well as a treatment of geologic folds see Lee and others (1974).

Thick, relatively uniform vegetation tends to obscure geologic features. This was especially noted on the higher slopes of the La Sal Mountains, where little geologic information could be interpreted from the relatively dark photographic tones, except for the general outline of an intrusive.

In central Colorado, only scattered observations have been made, mostly on 190A positive transparencies. Interpretation of Skylab photography is relatively difficult here, mainly because of obscuring effects of dense vegetation, but also because of variable snow cover and often widespread scattered cloud cover. In areas of minor vegetation cover,

as in northwest and southeast Colorado, favorable geobotanical associations may facilitate photogeologic interpretation. In the mountainous, mostly densely vegetated area of central Colorado, only very general contacts, such as contacts between sedimentary/igneous-metamorphic, volcanic/igneous-metamorphic, or, in some cases, volcanic/sedimentary rocks, can be readily interpreted. The igneous-metamorphic Precambrian complex can be discriminated, where sufficient areal exposures exist, by its distinctive fracture pattern and by its resistance to erosion. Good exposures are required for differentiation within sedimentary rock units. Little such differentiation is possible in the more densely vegetated areas, except where units have pronounced and variable topographic expression. In sparsely vegetated areas with good exposures, as in the Canon City embayment, several sedimentary rock units can be differentiated, mostly by topographic expression and, to a lesser degree, by contrasting color tones. Some inferences as to probable composition of the rocks can be made by use of these same criteria.

Several major faults can be interpreted from Skylab photography in central Colorado, but in the densely vegetated areas, only major faults with significant topographic expression can be readily interpreted as distinct from a general category of lineaments. Further investigation and familiarity with the photography and the area may

allow interpretation of less well expressed faults. Numerous, often well-expressed lineaments are present on much of the Skylab photography and ERTS-1 imagery. Many of the better-expressed folds are obvious on the Skylab photography. Estimates of bedding attitudes have not yet been done in any detail here, but in general, such estimates are more difficult in the densely vegetated terrain.

Numerous geomorphic landforms can be recognized on the Skylab photography, including such obvious features as hogbacks, cuernas, mesas, alluvial fans, etc., and less obvious features such as lateral and terminal moraines, cirques, pediment remnants, suggestions of erosion surfaces, igneous dikes, etc.

#### New Information

New information is, so far, restricted to the demonstrated feasibility of estimating bedding attitudes, with subdivision into different, although presently overlapping, categories, and carrying this photogeologic dip estimation down to dips of 1-5°, including detection of 1° dip reversals on a regional dip slope of 3-5°. This was done with a simple mirror stereoscope in an area of very good exposures on 4X positive transparency enlargements of the 190A photography. Further investigation is planned.

## Further Study

The main thrust of planned future work will involve an investigation of the tectonic significance of lineaments interpreted from Skylab and ERTS-1 images. The planned primary study area includes central and western Colorado and eastern Utah. The study will begin with interpretation and annotation of lineaments on Skylab and ERTS-1 images, and transfer to base maps at scales of 1:500,000 and 1:250,000. Comparisons will then be made with lineaments interpreted from shaded plastic relief maps, as well as available geological, geophysical, and previous lineament studies. Representative lineaments and individual study areas will be selected for further study with other remote sensing and field techniques. Remote sensing methods will involve mainly photogeologic interpretation of conventional aerial photography, both now at CSM and some to be acquired in the future. Other remote sensing methods such as LSAP, SLAR, and thermal infrared imagery will be utilized where available. Some aerial reconnaissance with a light plane is planned for selected lineaments, to be followed by field studies, mainly large-scale geologic mapping, but possibly including geophysical surveys and local joint studies. The entire investigation will focus on the expression, origin, and tectonic significance of regional lineaments, in sufficient detail to help explain,

and possibly use, lineaments in regional geologic investigations.

An attempt will be made to relate regional lineaments to tectonic elements, as well as with economic factors such as metallic mineral, hydrocarbon, and geothermal resources.

Several secondary study areas will be selected for a less detailed evaluation of lineaments in differing geologic terranes.

EVALUATION OF SKYLAB PHOTOGRAPHY.  
FOR DETAILED GEOLOGIC MAPPING

This is an evaluation of the use of photography in detailed geologic mapping in an area of high relief. The area under consideration is about 40 square miles in the San Juan Mountains of southwestern Colorado (geology of this area is described in Spoelhof, 1974). Low- and high-altitude color and color infrared aerial photography, black-and-white ERTS imagery, and Skylab color photography were examined to determine the accuracy of geologic mapping with each type of image. In particular, the questions asked during examination of the photos were:

1. Can significant details of the geology in the area be seen?
2. Can more details be seen than are recognizable on standard black-and-white aerial photographs?
3. Does use of the remote sensing data add to the speed with which mapping can be accomplished?

The examination of the images and the answers to the above questions are from the point of view of a field geologist who lacks training in remote sensing. Thus, this report is a subjective evaluation of the usefulness of images as tools for field mapping. This report should be of value to other geologists who wish to increase the accuracy and efficiency of their field work.

## Low-altitude Black-and-White Aerial Photography

It was desired to construct a geologic map of the study area at a scale of 1:24,000. The mapping was originally accomplished by plotting observations on 1:20,000 U.S. Forest Service aerial photographs. The photographs were primarily used to pinpoint station locations and to map geologic structures and lithologic contacts between station points.

The main difficulties encountered in using the black-and-white photographs were: 1. Inability to discriminate aspen trees from surrounding grass-covered areas, 2. Inability to discriminate between limestone and sandstone outcrops, and 3. Inability to map any geology in areas of extensive tree cover. This latter difficulty was partially alleviated by using larger scale (1:10,000) black-and-white enlargements.

## Low-altitude Color Photography

Near the end of the project, NASA Mission 213 color prints were used in the field as an aid to mapping on black-and-white photos. Initially, the color photography was used only to discriminate yellow aspen trees from surrounding grey-green grass areas, and so allow for more accurate station locations. It was noted, however, that

it was possible to discriminate large areas of grey limestone units that are interbedded with tan-weathering sandstone. It was thus possible to perform rapid studies of the distribution of gross rock types. In addition, since the limestone units are considered to be time-stratigraphic units, the mapping of limestone units means that it was possible to map time lines on the color photographs.

Since the black-and-white and color photography are nearly the same scale (1:24,000), no lineaments were recognized on the color photos that had not already been noted on the conventional photographs.

#### High-altitude Color Photography

Color photography from NASA Mission 248 proved very useful for rapid mapping of sedimentary rocks and geologic structures. Significant details that could be seen on the low-altitude photographs could also be seen at the scale of the high-altitude photography (1:100,000). Additionally, several lineaments were recognized on the smaller scale photography than had been previously noted. The lineaments may reflect faults that were not recognized in the field, but should have been checked.

It is recommended that the high-altitude photography be examined and interpreted before beginning any detailed

field mapping. The scale of the photography allows for rapid examination of a rather large area on a single photograph, photogeologic interpretation can delineate areas where ground work is needed, and lineaments that should be checked during the field work are expressed on the photos.

#### ERTS Imagery

ERTS imagery does not appear to offer advantages for detailed field mapping in mountainous areas. Because relief is very high in the study area, drainages are controlled more by topography than by lithologic changes. The scale of the ERTS imagery (1:1,000,000) is small, and the imagery cannot be used to delineate small topographic changes that reflect changes in the bedrock geology.

Examination of ERTS imagery of an area south and west of the San Juan Mountains, however, showed that the imagery can be useful for geologic mapping in areas of low topographic relief. Nearly all the lithologic contacts on the state geologic map (1:500,000) could be recognized on the ERTS imagery. No contacts could, however, be traced from areas of low relief into mountainous areas.

ERTS imagery is not recommended for geologic mapping at scales of 1:24,000.

## Skylab Photography

Double enlargements of Skylab color transparencies of the study area were examined briefly. The area with which the investigator is most familiar was, unfortunately, completely snow covered at the time the photographs were taken. Only a topographic change at the top of pre-Pennsylvanian sediments could be seen.

In areas south of the study area, where there was no snow cover, the Skylab data showed many significant details of the geology. In particular, the photos clearly distinguish upper Paleozoic redbeds from underlying light-colored rocks. The light-colored rocks can also be distinguished from Precambrian metamorphic and igneous rocks by the presence of joint patterns in the Precambrian rocks. All areas of outcrop can be easily distinguished from vegetated areas.

The primary limitation of the Skylab imagery is the small scale of the original photos. At that scale (~1:1,000,000), only major geologic features can be mapped, and then with not very great accuracy. Skylab photography is, however, useful for the field geologist who is working on a detailed mapping problem, in that the photos allow for rapid extension of major geologic structures outside a small study area. It should not be anticipated that Skylab data will yield any additional information about small areas.

## Summary

The most efficient way to carry out a detailed field-mapping problem in a previously unknown area would be to:

1. examine and interpret NASA high-altitude color aerial photography to obtain gross structural and lithologic patterns;
2. perform detailed photogeologic interpretation of NASA low-altitude color aerial photography to verify and expand the detail of the geology observed on the high-altitude photos, and establish working time-stratigraphic units;
3. use the low-altitude photography as an aid to field work;
4. use orthophotos or greatly enlarged Skylab photos to aid in compiling the field data and photo interpretations onto topographic maps,
5. extend local geology into a regional summary by using Skylab data.

Such a procedure would produce the most complete coverage of a small study area, and all significant details will have been examined. Less time would be required in the field since prior photo interpretation would have delineated areas that need to be checked in the field.

The primary utility of Skylab photography for geologic mapping in montane areas is clearly limited to regional mapping at scales smaller than 1:24,000.

## APPLICATION OF EREP DATA TO MINERAL EXPLORATION

### Objective and Rationale

The objective of this research is to utilize and evaluate Skylab EREP data, and to a lesser extent, ERTS and aircraft data, to locate indicators of mineralization in central and southwest Colorado. The reason for such a study is that it is economically more desirable to survey large areas for potential mineralization by remote sensing than by conventional ground surveys. The advantages of satellite photography and imagery are the synoptic view, repetitive coverage, accessibility to remote areas, and relatively low cost. Despite the desirability of locating potentially economic targets quickly and inexpensively, it must be stressed that field work is always required for verification; it is merely hoped that needless field work may be eliminated.

Indicators of mineralization that can be seen on satellite images are structural features and anomalous colors. "Anomalous", as used here, means a local feature that deviates from a regional uniformity; a feature considered capable of being associated with commercially valuable mineral deposits. Vegetation patterns may be indicators of mineralization, although preliminary study

shows they are probably not significant. This research is based on the assumption that indicators of mineralization can be seen on multiband, color, and color-infrared satellite photography, and on multispectral satellite imagery. During the course of the study this premise will be either proved or disproved.

### Study Areas

The area being studied for potential targets is outlined by Frame 17, Skylab 2 S190-A (multiband) photography from Track 48, 11 June 1973, and by Frames 106 and 107, Skylab 3 S190-A from Track 48, 4 August 1973. The area is also covered by Frames 38 and 39, Skylab 3 S190-B (high resolution) photography from Track 48, 4 August 1973; by Frame 172-17141, ERTS-1 imagery from 11 January 1973; by Frame 154-17143, ERTS-1 imagery from 24 December 1972; and by several aircraft underflights, most notably NASA missions 205, 211, 213, and 235. The entire survey area covers approximately 18,000 square miles (46,800 km<sup>2</sup>) of central Colorado (Fig. 3).

The S192 is an integral part of the Skylab experimental package, yet there is no S192 coverage of the central Colorado survey area. Therefore it is felt that an area with a wide variety of landscapes, lithologies, and vegetation types that has S192 coverage should also be evaluated. In addition to the survey and target areas mentioned above, a

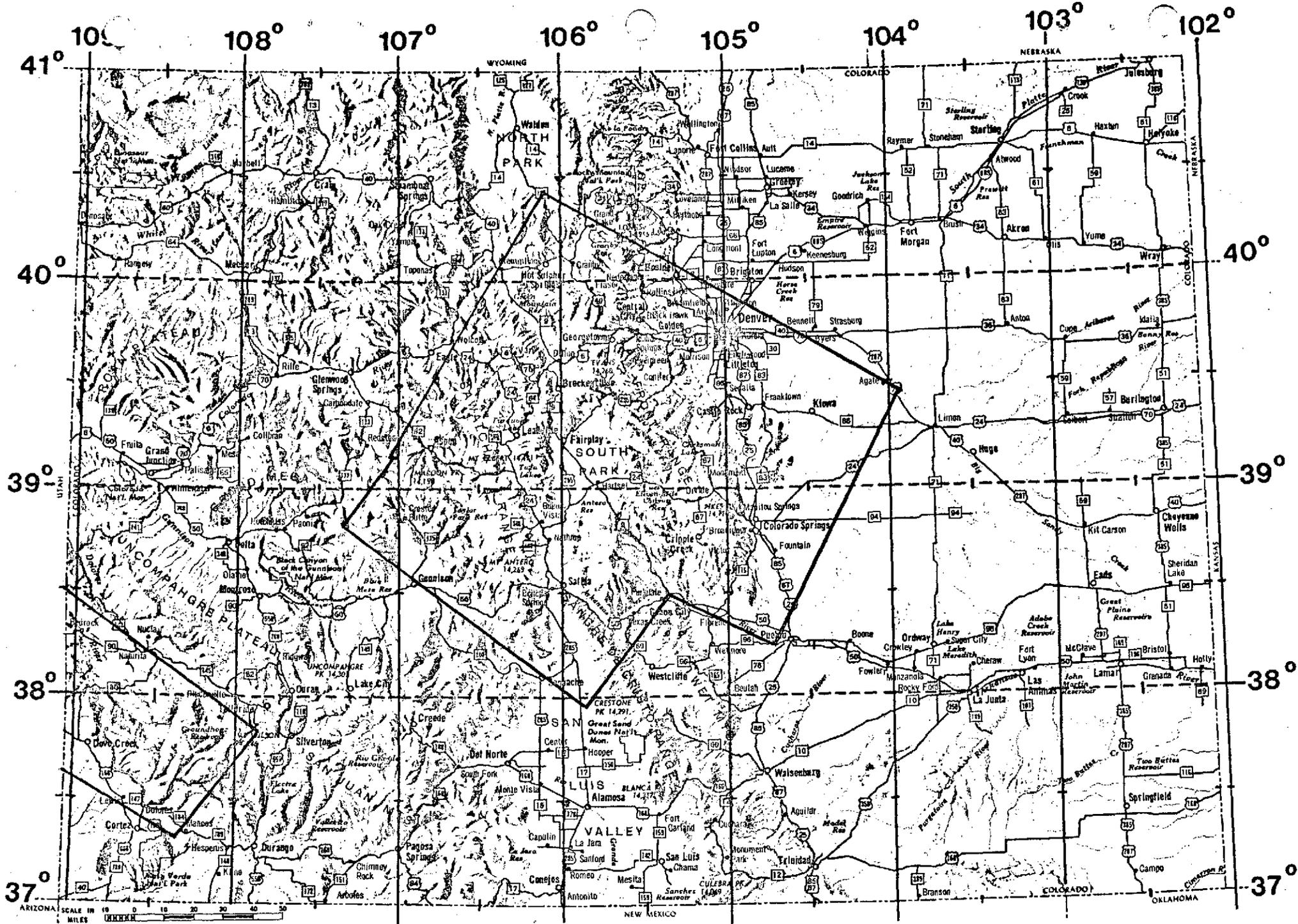


Figure 3. Central Colorado Survey Area; Southwest Colorado Test Site

southwestern Colorado test site has been designated for the evaluation of the S192 multispectral scanner (Fig. 3).

The area in Colorado covered by the S192 is approximately 2800 square miles (7,280 km<sup>2</sup>).

#### Results to Date

The geology of the Leadville and Cripple Creek mining districts was studied as typical of the kinds of mineralization that can occur in central Colorado. At the same time, the Skylab photos covering these areas were observed in an attempt to correlate geology from maps to the photographs. Each area was checked on the ground to identify exactly what was interpreted from the photography. The two control districts were analyzed to determine which geologic features are characteristic of the mineralized areas, and which of these features in turn are visible on the satellite photography. Various enhancement techniques were tried in an attempt to make all of the indicators of mineralization obvious.

Study of the Leadville district reveals that ore deposits are chiefly in shattered rock within fissure zones or in beds of Ordovician limestone that have been intruded by Upper Cretaceous or Lower Tertiary felsic to intermediate porphyries. Faults themselves contain ore in only a few places, while auxiliary faults and fissures along them are

mineralized and have served as feeders to replacement orebodies (mineralization has also been related to karst solution features in the Leadville dolomite paleotopography). Alteration includes local hydrothermal bleaching of porphyries and weathering of disseminated pyrite. Indicators of mineralization for this district are faulting, intrusion of sedimentary strata and thrusting aside of sedimentary blocks by light-colored porphyries, bleached intrusions, and weathered pyrite. Field checking verified the ability to see alteration colors on Skylab photography.

Study of the Cripple Creek district shows that ore deposits are within or at the margins of a steep-sided basin (caldera, breccia pipe?) filled with Miocene breccia and surrounded by Precambrian granite, gneiss, and schist. The basin, approximately two miles by four miles, is filled with volcanic as well as non-volcanic debris, and is cross-cut by dikes of phonolite and lamprophyre. It has been determined that the basin is fault-caused, not volcanic, although it did serve as the locus for intense igneous activity. Mineralization followed recurrent fissuring and consists of veins and fissure fillings, with pyrite a common mineral. Indicators of mineralization for this district are faulting, basins of breccia cut by dikes, and alteration of pyrite. Field checking revealed, however, that photo-color anomalies, in this area at least, are more likely a result of pink microcline in the Precambrian granite.

Weathered pyrite is seen only on the mine dumps, which also are very visible on the photography.

Indicators of mineralization that can be seen on satellite photography over the Leadville and Cripple Creek mining districts are faulting, intrusion of light-colored porphyries into bedded sediments, weathering of pyrite, and hydrothermally bleached intrusives. It is almost impossible to see local thrusting of sedimentary blocks and breccia-filled basins cut by dikes.

The central Colorado survey area was studied in an attempt to locate all indicators of mineralization. These locations (targets) were plotted on a master map of the area, and these were ranked from most to least likely mineralized (Fig. 4). Targets were located by mapping lineaments as guides to faults, and color anomalies as guides to intrusions and alteration. Four lineament overlays were made, one for each of the following:

- 1) 9x9" pos. color-infrared (CIR) transparency of Frame 17, Track 48, Skylab 2, S190-A,
- 2) 7x7" neg. CIR print of fr. 106, tr. 48, S.L. 3 S190-A, and 7x7" neg red band print of fr. 107, tr. 48, S.L. 3 S190-A,
- 3) 9x9" color prints of fr. 38 and 39, tr. 48, S.L. 3 S190-B,
- 4) 7x7" red band print of pos.-neg. slip masks made from fr. 17, tr. 48, S.L. 2 S190-A, and fr. 106 and 107, tr. 48, S.L. 3 S190-A.

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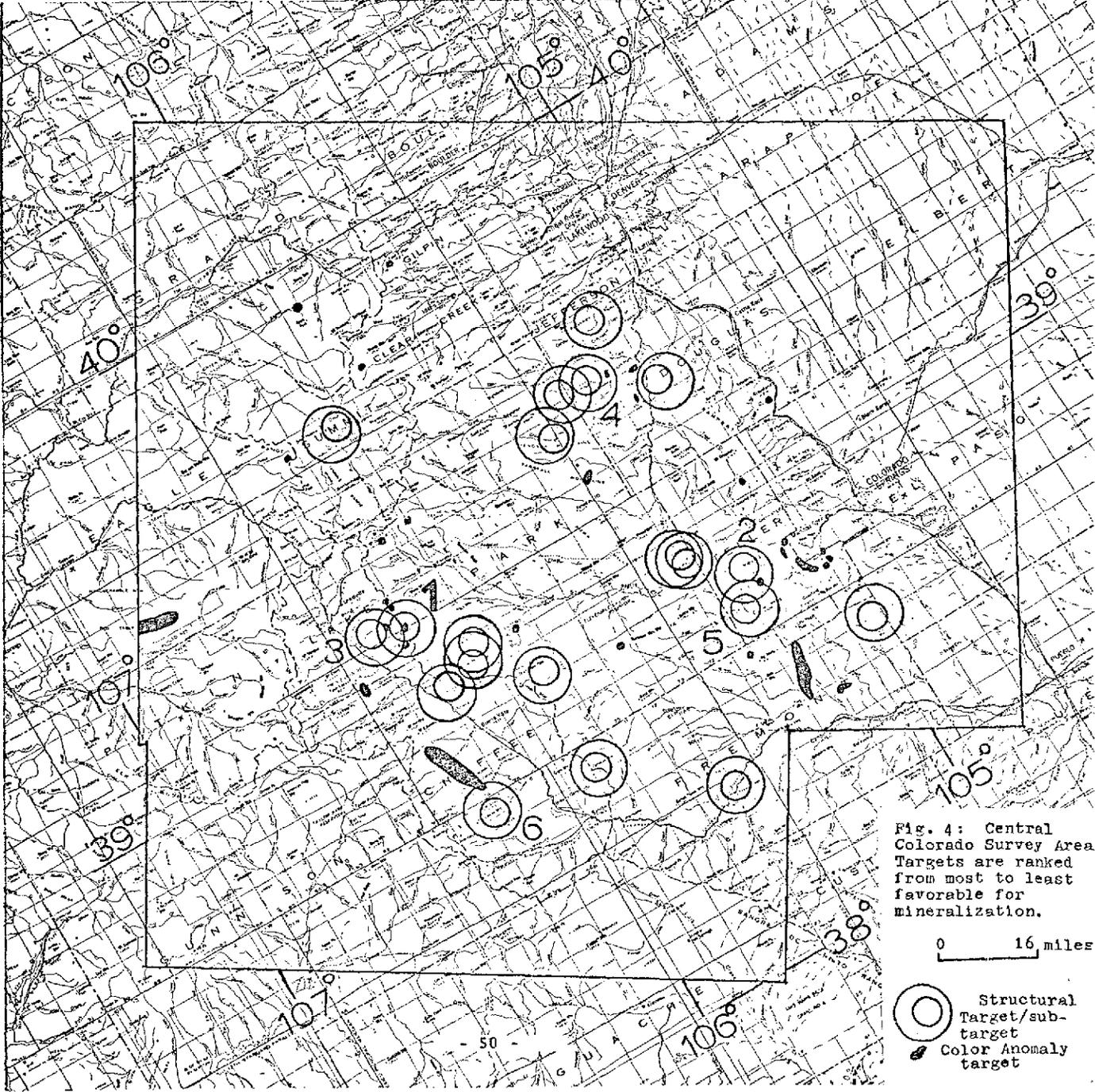


Fig. 4: Central Colorado Survey Area Targets are ranked from most to least favorable for mineralization.

0 16 miles

- Structural Target/sub-target
- Color Anomaly target

Everything that appeared unquestionably linear was marked as a solid line, while questionable linears were dotted. Care was taken to not include man-made or cloud-caused linears. Targets are those areas with a high density of lineaments and lineament intersections.

Color anomalies were observed by color-additive viewing of Frames 106 and 107, Track 48, Skylab 3 S190-A, and by viewing Frames 38 and 39, Track 48, Skylab 3 S190-B. No color anomalies were seen on unenhanced S190-A photos, nor were any noticed on the diazo color-coded density slices. The possible color anomalies were divided into types A (red to orange), B (light rock surrounded by darker rock), and type C (dark rock surrounded by lighter rock). No type C anomalies were found. The color anomalies were plotted on 1:250,000 topographic maps. Each was considered a target.

Targets were then transferred from the photolineament and color anomaly maps to a master map. Areas considered most likely mineralized (second generation targets) contain both color anomalies and a high density of lineaments. These second generation target areas were ranked from best to worst according to these criteria. The targets arbitrarily are circular areas with a radius of four miles ( $6.4 \text{ km}^2$ ), enclosing an area of approximately 50 square miles ( $130 \text{ km}^2$ ), and within each is an alternate subtarget, a circular area with a radius of two miles ( $3.2 \text{ km}^2$ ), enclosing an area of about 12.5 square miles ( $32.5 \text{ km}^2$ ). The highest priority targets will be mapped at a scale of 1:24,000, and their subtargets, at a scale of 1:12,000.

The most favorable target/subtarget will become the prime experimental area for this study. It would be significant to learn whether two areas some distance apart, characterized by the same indicators of mineralization, do indeed contain such desired features. Therefore, targets other than the primary may be briefly evaluated as to their indicators of mineralization.

If the interpretations so far are correct, that is, if faulting, intrusion, and alteration have been accurately mapped on satellite photography, then ground mapping and sampling will prove that indicators of mineralization can be quickly and economically found.

#### Plans For Continued Study

Future research will include a comparison of Skylab photography and imagery to ERTS imagery with respect to finding indicators of mineralization; an evaluation of unenhanced and enhanced S192 imagery with respect to finding indicators of mineralization; mapping of geologic features from medium and/or low altitude aircraft photography and an evaluation and comparison of this information with that from Skylab data, and checking target areas by field mapping and sampling.

APPLICATION OF EREP DATA TO  
VOLCANO-TECTONIC-METALLOGENIC STUDIES  
SAN JUAN MOUNTAINS

Skylab-2 color and color infrared photography of the San Juan Mts., Colorado, has disclosed several systems of linear fractures both subparallel and intersecting. Caldera development seems to have occurred at several intersections of the larger, longer linears. Several, dome-like, considerably smaller structures, possibly laccolithic, occur along and tangent to linears but not at the intersection of linears.

Base metal and precious metal vein deposits are not apparently structurally controlled by these major linear systems, but have a time-span, time-space relation to structural positioning and volcano-tectonic development of calderas located at intersections of some of the larger linear systems.

Regional studies using low-altitude aerial photography, color, and black and white are complicated by the large numbers of photos requiring examination and by the fact that large regional features may be masked by, or may form the background for, finer detailed features. Skylab-2 provided accurate, small-scale photographs of a large segment of the San Juan Mtn. region on which many of the finer

detailed features are not well defined, and the regional characteristics thus are emphasized or are easier to detect. Both EREP photos and ERTS images are being interpreted and used in this study, along with supporting aircraft under-flight data.

### Lineaments

Linear features include aligned streams or segments of streams, aligned offsets along several adjacent streams, aligned tributaries over rather long distances, and erosion cuts across summit and divide areas. Those photographic linears thought to indicate possible fracture, joint, or fault systems are termed "lineaments". Breaks in bedding in sedimentary rocks occurred only on one lineament; all other lineaments seem to occur in crystalline plutonic igneous, metamorphic and volcanic units.

Although the criteria used to define the lineaments are those commonly used to define fractures, joints, or faults from photographs, the geologic reason for most of the lineaments observed on the Skylab-2 and ERTS-1 imagery is not as yet specifically known. These linear features are thought to be geologically controlled, but a geologic explanation for them should be investigated in the field.

### Lineament Systems

The lineament patterns may be divided into several lineament systems, defined on the basis of their surface

trends and their relation to adjacent systems. Some of the systems are parallel with the topographic grain of the area. Other systems cut across the topographic grain or are oblique to it.

Throughout the 8000 square mile area of the San Juan Mts. studied on Skylab-2 and ERTS-1 images, twenty-three (23) lineaments have been mapped. Names for these lineaments have been assigned using topographic and cultural features such as streams, rivers and towns located along or adjacent to the lineaments.

The Rico-Silverton-Cebolla Creek-Los Pinos-Cochetopa Park Lineament is the longest and strongest lineament dominating the San Juan Mtn. region. It is 97 miles long and trends an average of N 65 E, with near-vertical dips. Another lineament is 72 miles in length, trends N 45 E, with near-vertical dips, and intersects San Luis Peak Caldera. Subordinate yet moderately strong lineaments occur in the southeast portion of the San Juan Mtn. area, trending N 40-45 E and ranging in length from 22 to 57 miles.

#### Lineament - Caldera Associations

Twelve of the seventeen lineaments in the central and west central part of the 8000 square mile study area intersect, or are tangent to, caldera structures visible of the surface. Dominating this structural scene is the

Rico-Silverton-Cebolla Cr ek-Los Pinos-Cochetopa Park 97-mile-long lineament. Aligned along and intersected by this lineament are the following calderas: Cochetopa Park, San Luis Peak, Lake City and Silverton. Razor Creek and Tomichi domes, probably laccoliths, lie at the extreme northeast end of the lineament and Rico Dome is at the extreme southwest end. All domes are on the northwest side of the lineament.

Regionally, the smaller dome-like intrusions, probably laccoliths, are situated along lineaments only, but the five mapped caldera structures are located at intersections of the stronger, more dominant lineaments.

#### Volcano-Tectonic Chronology

Attempts at placing a geochronological parameter (time-space and time-span dependency) on lineaments associated with domes and calderas must be based on "existing ground truth" of lineaments, either as actual zones of movement or as linear fold axial trends, or as both. Some field evidence exists in several areas for actual movement along lineaments.

Field evidence and absolute age determinations show all five calderas and all (except one) of the domes are post-Telluride Conglomerate in age - i.e., post-late Eocene to early Oligocene. If the intersecting lineaments and fold axes served to control the development of calderas

and domes, not only must these structures be pre-late Eocene in age, but the thought is, of course, that prior-existent, primitive, possibly Precambrian age structural flaws were inherited to be rejuvenated prior to and during the Cenozoic volcanism. Field evidence confirming this time-space and time-span chronology needs to be obtained to support the validity of the volcano-tectonic sequence so far indicated by Skylab-2 and ERTS-1 image analysis.

#### Volcano-Tectonic-Metallogenetic Model

Inherent in this study has been the hope that centers of base metal-precious metal vein deposits and the more recently-discovered replacement deposits may be metallogenetically related to development of the calderas. For this reason, low level, relatively large-scale black-white and color photography have been used to define greater geological detail in selected areas. So selected was the Telluride-Ouray-Silverton Caldera area in which there is an extremely strong development of base metal-precious metal vein deposits and replacement ore deposits.

Surficial and underground mapping within the Telluride-Ouray-Silverton Caldera triangle indicates the presence of three separate, distinct fracture sets formed during rise, emplacement, collapse, resurgence and collapse of Silverton Caldera. In order of formation, these are (1) radial-concentric compressional-dilational fractures, (2) concentric,

inward dipping cone-sheet like fractures related to caldera collapse, and (3) epicycloidal tangential shears also related to caldera collapse.

Field and laboratory studies of fracture development, vein-trends, alteration patterns with associated mineral paragenesis within the Telluride-Ouray-Silverton Caldera area are being reported on separately.

One of the greatest values of Skylab photography, to date, is that it serves as a medium of structural definition superior to field inspection techniques for observing relatively large segments of the earth's surface. The structural domains so defined, especially in the instance of the San Juan Mountains, with their intimate relationship of metalliferous ore deposits to large volcano-tectonic structural domains, enables the geologist to very rapidly define a volcano-tectonic model and to also evaluate it practically in relation to existing structural-tectonic-metallogenetic parameters.

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