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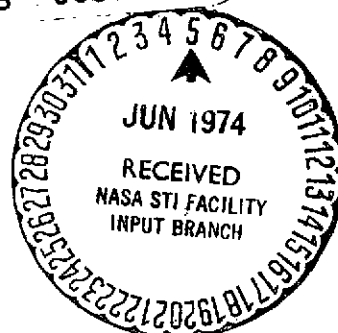
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GEOLOGIC INFORMATION FROM SATELLITE IMAGES

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DEPARTMENT OF GEOLOGY

COLORADO SCHOOL OF MINES ★ GOLDEN COLORADO

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ABSTRACT

Extracting geologic information from ERTS and Skylab/EREP images is best done by a geologist trained in photo-interpretation. The information is at a regional scale, and three basic types are available: rock and soil, geologic structures, and landforms. Discrimination between alluvium and sedimentary or crystalline bedrock, and between units in thick sedimentary sequences is best, primarily because of topographic expression and vegetation differences. Discrimination between crystalline rock types is poor. Folds and fractures are the best displayed geologic features. They are recognizable by topographic expression, drainage patterns, and rock or vegetation tonal patterns. Landforms are easily discriminated by their familiar shapes and patterns. Their regional presentation enhances physiographic studies. It is possible to optimize the scale, format, spectral bands, conditions of acquisition, and sensor systems for best geologic interpretation. Several examples demonstrate the applicability of satellite images to tectonic analysis and petroleum and mineral exploration.

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K. LEE, D.H. KNEPPER, D.L. SAWATZKY

INTRODUCTION

Most geologic information will eventually be extracted from space data by geologists without specialized training and without sophisticated data processing equipment. The extraction of geologic information from ERTS and Skylab/EREP images is still a deductive process, involving the geologist-interpreter. The validity of interpretations will therefore depend upon the experience of the geologist in deducing pertinent geology from surface features, and it is imperative that the interpreter understand how those surface features appear on space images and how best to use the images ("space images" are taken to include both scanner imagery and photographs, acquired from space by satellites in earth orbit).

The type of geologic information that can be extracted consists of rock discrimination, geologic structures and landforms - the same as with conventional aerial photography - but the geologic features will, of course, be on a regional scale.

The authors are geologists with experience in geologic remote sensing from aircraft and from spacecraft, mostly in the Colorado Rocky Mountains, and the discussions that follow are based on experience in that area. All illustrative examples are from the Rockies, and consequently do not represent the spectrum of geologic terrains over which ERTS and Skylab images have been acquired. However, the statements and conclusions probably apply to images from much of the world, and the principles, at least, can be transferred easily to other geologic settings.

The following sections of this paper will discuss (1) basic geologic information contained in satellite images, the surface expressions of geologic features and how they appear on satellite images, (2) recommended approaches to the use of satellite images, and (3) some preliminary examples of the application of space data to geology.

GEOLOGIC INFORMATION FROM SATELLITE IMAGES

BASIC GEOLOGIC INFORMATION

Geologic analysis of ERTS and Skylab/EREP images involves the extraction of specific types of information basic to all geologic investigations. This basic geologic information consists of determining the location and distribution of:

1. rocks and soils (lithology)
2. geologic structures (folds and fractures)
3. landforms.

Basic geologic information must be interpreted from ERTS and Skylab images by reading the tones, textures, and geometrical relationships between tones and textures in terms of physical parameters of the earth's surface. The ability to extract basic geologic information from space images depends, in large part, on two primary considerations:

1. How well the information is expressed at the surface, and
2. How well the surface expression is translated to the imagery.

Lithologic contacts, geologic structures and landforms are represented at the earth's surface by changes in 1) color, 2) topography, and 3) vegetation. It is difficult to place exact figures on the changes in color, topography, and vegetation that are necessary in order to be interpreted on ERTS and Skylab images, since all three parameters almost always change together with a change in geologic conditions. In addition, it must be understood that changes in color, topography, and vegetation all serve to change the tone (color) and texture on space images, and it is difficult or impossible in most cases to attribute a change in tone or texture uniquely to one of the parameters alone without extensive ground data. Suffice it to say the minimum "changes" in color, topography, and vegetation that can be mapped on ERTS and Skylab images are quite variable.

The minimum size of geologic features that can be mapped on space images is equally difficult to quantify because mappability depends both on size and contrast. For a given tonal/textural contrast, however, narrow, linear features such as steeply-dipping sedimentary beds, fractures, and dikes are more easily mapped than small, equidimensional features.

In all respects, the tools and skills of the photointerpreter are absolutely prerequisite for analyzing space images, because the interpretation of basic geologic information from small-scale images involves an understanding of many types of indirect information (e.g. - drainage pattern, type, and texture, vegetation distribution and density, land use patterns, etc.). The necessity of interpreting many kinds of indirect features for geologic information on space images severely limits the utility of automated geologic mapping of the imagery by machines--at the present state of the art it is not possible to train a computer to make all the decisions that a photo-geologist must routinely make during the course of geologic interpretation. Hence, the extraction of geologic information from space images remains in the realm of the human interpreter, and we shall discuss the various aspects of basic geologic information in terms that hopefully will be useful to the practicing geoscientist.

LITHOLOGY

A primary objective of all forms of geologic mapping is the determination of the distribution of rock types and soils (including alluvial material). On relatively large-scale photos (1:10,000-1:50,000), lithologic units can be discriminated (and commonly can be identified to some degree) by considering tone or color and texture, among other factors. The relatively large resolution elements of ERTS and Skylab images commonly preclude lithologic identification except in those instances where lithology can be derived by considering the

shape and form of the unit (e.g. - volcanic cones and flows, glacial deposits, alluvial fans, pediments, etc.). However, there are many instances where at least a gross identification can be made (e.g. - resistent sedimentary rocks, fractured crystalline rocks, etc.), and the photo-interpreter is obligated to make these tentative identifications where possible.

The easiest and most consistent lithologic discrimination that can be made on space images is between alluvium covering valley floors and bedrock exposed in bordering uplands. These two types of lithologic terrain differ greatly in topography (micro-relief at the scale of space images) and type and amount of vegetative cover. Areas underlain by bedrock have moderate to high local relief and are commonly covered by coniferous forests. Alluviated areas, on the other hand, are relatively flat and are most commonly covered by grass and small shrubs. These topographic and vegetative differences are easily identified on space images because of the distinctive tonal and textural patterns they produce (Fig. 1).

Lithologic discrimination between bedrock units is more difficult and depends greatly upon the type of bedrock involved. Discrimination is generally best between lithologic units within thick sequences of sedimentary rocks. Where the sedimentary rocks are moderately- to steeply-dipping, lithologic contacts are enhanced by the effects of differential erosion, producing long, linear outcrop bands. Tonal (color) and textural contrast between outcrop bands on the space imagery is enhanced if the spectral reflectance of adjacent units is highly contrasting, or if the units are selectively different in their support of vegetative growth.

Areas underlain by crystalline rocks (extrusive and intrusive igneous rocks and metamorphic rocks) can generally be discriminated from areas underlain by sedimentary rocks or covered by alluvium, but discrimination within crystalline
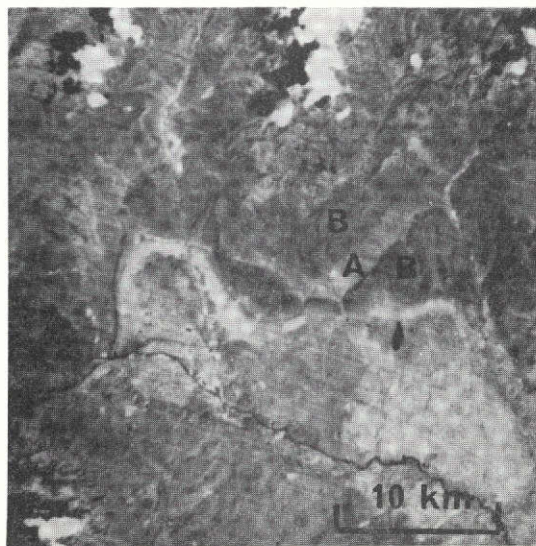
GREEN (500-600nm)
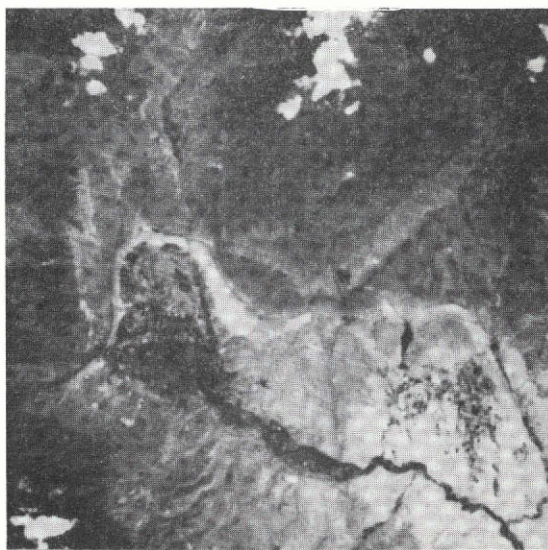
RED (600-700nm)

IR (700-800nm)

IR (800-1,100nm)

Figure 1: ERTS MSS imagery of the Canon City,
Colorado, area. A, alluvium; B, bedrock.

terrain is very poor and identification virtually impossible on space images. The general inability to discriminate between crystalline lithologic units probably stems from two factors:

(1) Crystalline rocks are relatively homogeneous in terms of resistence to erosion, at least at the scale of space images.

(2) Although crystalline rocks in Colorado vary greatly in composition, which should be reflected in selective vegetation growth, the crystalline rocks are exposed only in the mountainous regions of the state where vegetation is more sensitive to elevation changes.

The spectral pass band of the images used for lithologic mapping is an important factor in lithologic discrimination in central Colorado, and probably other areas as well. Where color photographs are available, especially from the S190B, they provide the best medium for mapping lithologies. Recent experiments on ERTS (MSS) and Skylab (S190A) images indicate that among black and white images, the red band generally is best for lithologic mapping, particularly when the image depicts a high sun-angle, snow-free scene (Fig. 1). However, the red band alone is commonly not sufficient for all lithologic mapping, and all available bands should be consulted to insure that the maximum amount of available lithologic information is obtained. No obvious advantage accrues to using two or more bands in register, since spectral reflectance differences of rock units do not appear to favor any one band over others (Raines and Lee, this publ.).

ERTS imagery from June, August, December, and January were studied to determine the mappability of lithologic contacts in central Colorado. Imagery acquired in June (spring) is far superior to the other imagery for lithologic mapping (Fig. 2). Each of the contacts studied is expressed topographically and shows a change in vegetation at the contact, and many of the contacts are

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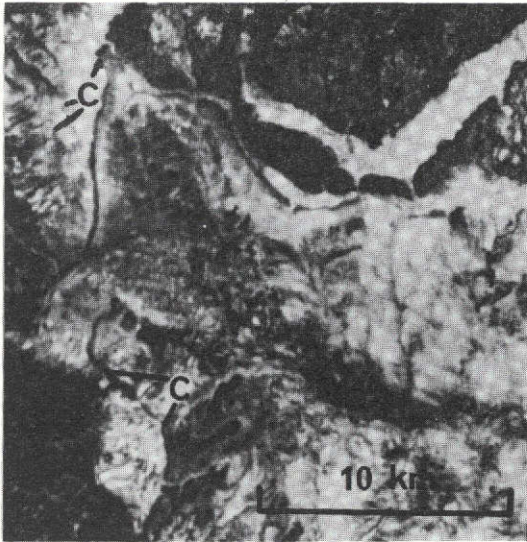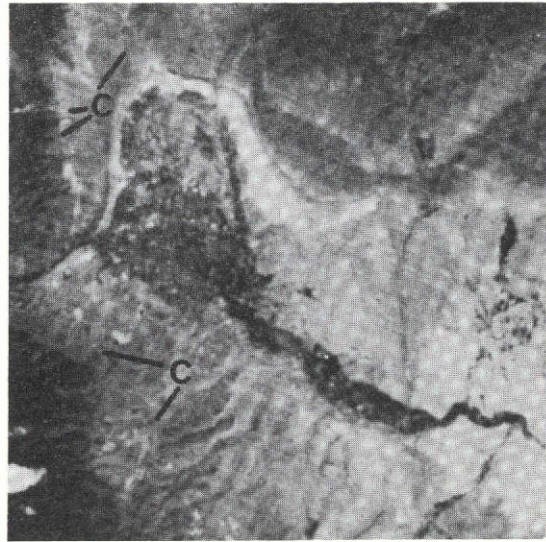
JANUARY   JUNE

Figure 2: Winter and spring ERTS MSS imagery of the
  Canon City, Colorado, area. C's are lithologic
  contacts located for comparison.

between units that are highly contrasting in
spectral reflectance. The fact that the June
imagery is superior suggests that vegetation ex-
pression overshadows topography and spectral
reflectance in defining the contacts on ERTS
imagery. In addition, it appears that the red band
better displays these vegetative differences than
do the green and photo-IR bands.

     Some of the contacts not expressed well on the
June imagery were very apparent on the winter
scenes (Fig. 2). Therefore, although the spring
imagery is generally the best, winter imagery must
also be used if the maximum amount of lithologic
information is to be extracted from ERTS imagery.
There is little difference between the lithologic
mapping capability of the red and IR bands of
winter (snow-covered) scenes.

FOLDS

     Space images are capable of yielding good
information on geologic folds. Although expression

of folds is not as obvious or dramatic as that of
lineaments due to fractures, their interpretation
can generally be made with more confidence. This
suggests that in well mapped areas, space images
will provide minimal new fold information, but in
poorly known areas they will yield reliable informa-
tion on new fold structures. Interpretation of
folds is not limited only to regional structures,
and structures need not be strongly folded.

Few folds are instantly recognized on images;
most are relatively subtle in expression and must
be carefully worked out. The surface expression
most useful in fold interpretations is topography
(and related phenomena). The majority of mappable
folds are worked out by determination of opposing
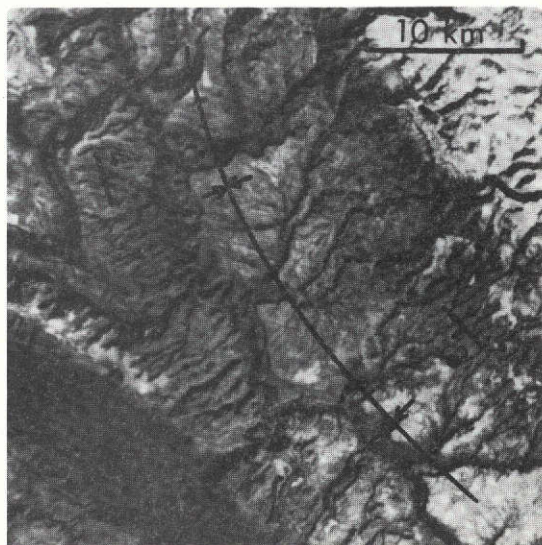dips (Fig. 3), with the dip interpretations based

Figure 3: Subtle expres-
sion of syncline,
determined by interpre-
tation of opposing dips.
ERTS Band 5.

largely on the recognition of topographic features.
Dip slopes may be directly recognized where stereo
viewing is possible. Without stereo, indirect
expressions helpful in slope interpretations are
shadow relationships and variations of vegetation
that are topographically-controlled. Drainage
patterns are indicators of slopes, and the drainage/
strata geometry (rule of V's) is the most con-
sistently useful criterion for determination of
dips (Fig. 4,A).

Some folds - generally plunging folds - are ex-
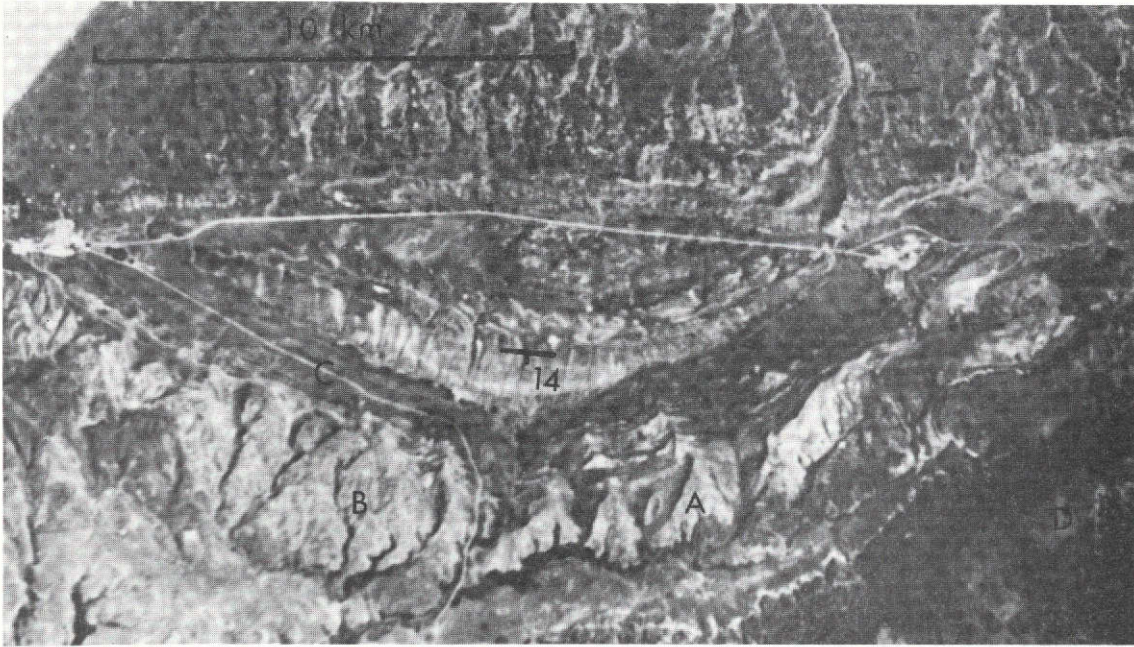pressed as tonal (or color) patterns (Fig. 5). Of

Figure 4: Folded and faulted Permian-Triassic sedi-
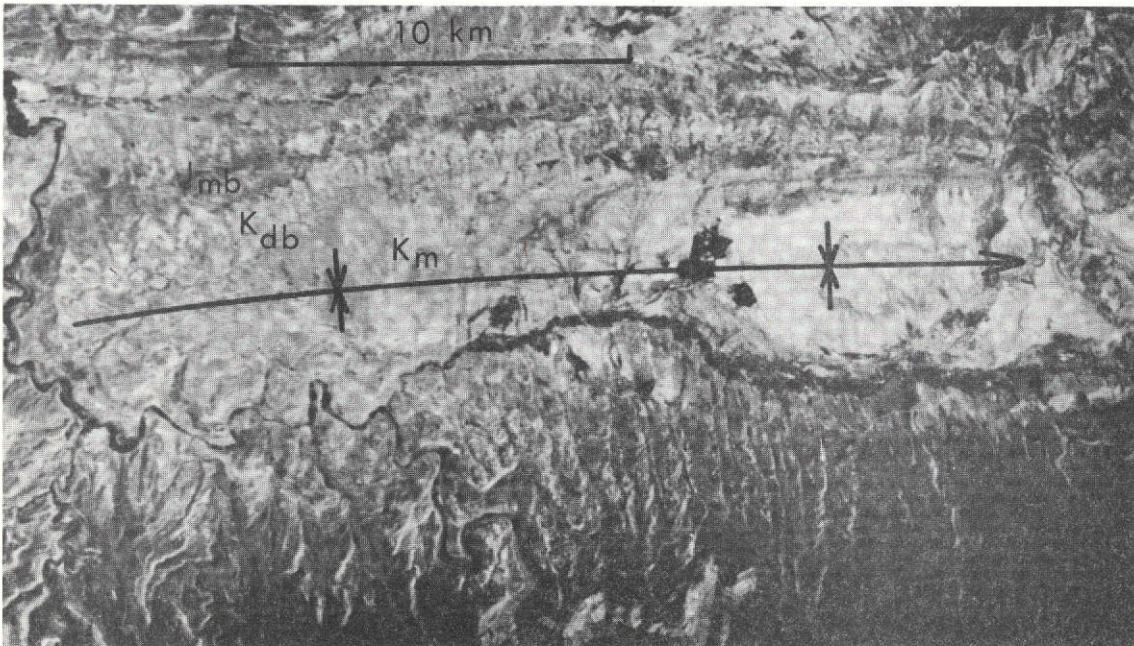mentary rocks. Skylab S190B color photograph.

Figure 5: Plunging syncline expressed by tonal pat-
tern. Jmb-Brushy Basin Shale, Kdb-Dakota and Burro
Canyon sandstones, Km-Mancos Shale. Skylab S190B
color photos.

these tonal patterns, some can be attributed to differences of spectral reflectance between contiguous strata, but this surface expression is probably subordinate to tonal differences related to topography. Topography can produce tonal differences in several ways. (1) Aspect angle (sun-target-camera) differences caused by topography are ubiquitous, and resulting tonal differences are common (Fig. 4,B). (2) Topographically low areas are generally sites of alluvial deposition, and alluvium-bedrock contrasts are often relatively great. (3) Elevation and slope direction control vegetation, often producing sharp boundaries between vegetated and nonvegetated areas and between different types of vegetation. Resulting large image tonal contrasts may then occur between vegetation-bedrock, vegetation-soil, vegetation-alluvium, vegetation-snow, trees-grass and conifer-hardwoods.

Relatively subtle folds can be mapped with confidence. Interpretation of ERTS red band imagery has yielded dip information (dip slopes) in the range of 3°-10° (Fig. 3); dips as gentle as 2°-6° have been observed on Skylab S190B photos (Fig. 4).

Interpretation techniques for using space images are the same as for conventional photo-geology using aircraft photos. An obvious difference is in the realization that small fold structures may not be mapped, but a compensatory difference exists in that broad folds may be seen (at least interpreted) in their entirety on one scene.

FRACTURES

Early interpretations and evaluations of space images have stressed the recognition of linear elements in the data. That an abundance of linears occurs on space data is apparent to any observer with geologic interests. Many of these linears are related to geologic phenomena, and many of the

geologically-controlled linears are related to
fractures.

Although fractures often are expressed on
space images as linear elements, which are more
obvious than most fold structures, their interpre-
tation is subject to greater uncertainty. Many
linears on space images cannot be interpreted, much
less identified as to geologic cause, and many
faults and joints cannot be found on space images,
even though they are of sufficient scale to be
easily resolved.

The corollary to these observations is that,
in areas that have already been mapped, fracture
information is likely to be the most significant
new information gained from photogeologic interpre-
tation of space images, but the information must
be extracted with difficulty and with uncertainty.

To avoid possible confusion in terminology,
the following terms are defined: a linear is
any line or alignment of features, straight or
slightly curved, and a lineament is a linear of
probable geologic control (the term denotes a
degree of interpretation). Linear elements known
to be geologically-controlled are designated by
their specific descriptive names - contacts, faults,
etc.

Space images provide a synoptic view of large
areas that permits the recognition of large regional
lineaments that in detail may be too subtly ex-
pressed to be recognized on aircraft images or in
the field. A second advantage that accrues to the
use of space images is the ability to recognize
and analyze the "fabric" of a region - that is, the
dominant trends of lineaments - that relates to the
tectonic framework.

The interpretation of fractures (taken to
include faults, fault zones, shear zones and joints)
is based mainly upon the interpretation of topo-
graphy and topographically-controlled phenomena such
as vegetation. Less common surface expressions

include the distribution and relationship of rock units (note that this is the primary field criterion), and vegetation directly controlled by fractures - generally by controlling availability of ground water.

Faults affect topography in several ways. Late Cenozoic faulting may produce primary land-forms (fault scarps). Faults that juxtapose rock units of differing erosional resistance will ultimately produce relief by differential erosion (fault-line scarps, Fig. 6). Faults within homogenous bedrock, as well as joints, commonly are mechanically weak zones that are more susceptible to erosion and consequently tend to form linear topographic lows.

The dominant image expressions of these topographic features are linear tonal contrasts induced by aspect angle changes. The commonest examples, perhaps, are the tonal contrasts associated with linear valleys where one valley slope is fully illuminated and the opposing slope is only slightly illuminated, or even fully shadowed (Fig. 7). Maximum contrast results from
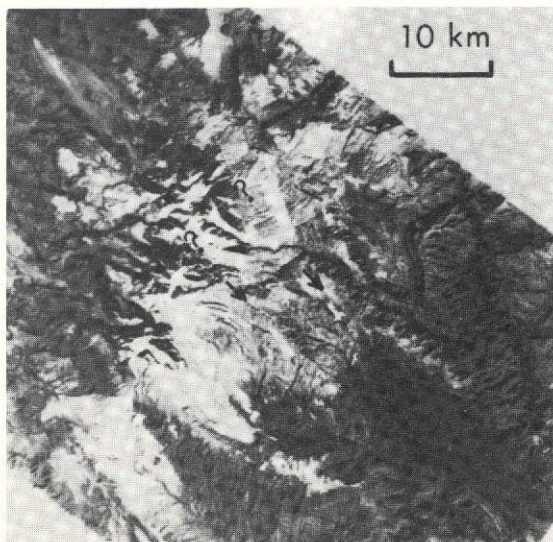

Figure 6: Fault-line scarps. Arrows indicate mapped faults, "?" are possible extensions. ERTS Band 5.

Figure 7: Zone of normal faults in Paleozoic sedimentary rocks. Skylab S190B color photo.

the latter condition, which obtains when the sun's rays are at grazing incidence on one of the slopes - that is, when the solar elevation angle is equal to the slope angle (Wise, 1969; Sawatzky and Lee, this publ.). This relationship is sometimes exploited in low sun-angle photography (LSAP) from airccraft. One significant difference between aircraft and spacecraft LSAP that is not commonly recognized, however, is that the optimum elevation angle is different. Basically, the optimum low sun angle is determined by the slope angles that one wishes to enhance. Relatively large-scale aircraft photography is concerned with small, local structural detail, and in areas of moderate to high relief, such as the Rocky Mountains, these structures are commonly expressed as small, fairly steep slopes. Optimum illumination angle in such a case may be 20°-30°; lower sun angles would tend to obscure large portions of the photography. In space photography, however, small, steep slopes are rarely recognized because they are rarely maintained for any considerable distance, and the slopes amenable to interpretation are usually more extensive. These larger topographic landforms have correspondingly lower average slope angles. For comparative examples, see Fig. 8, which shows
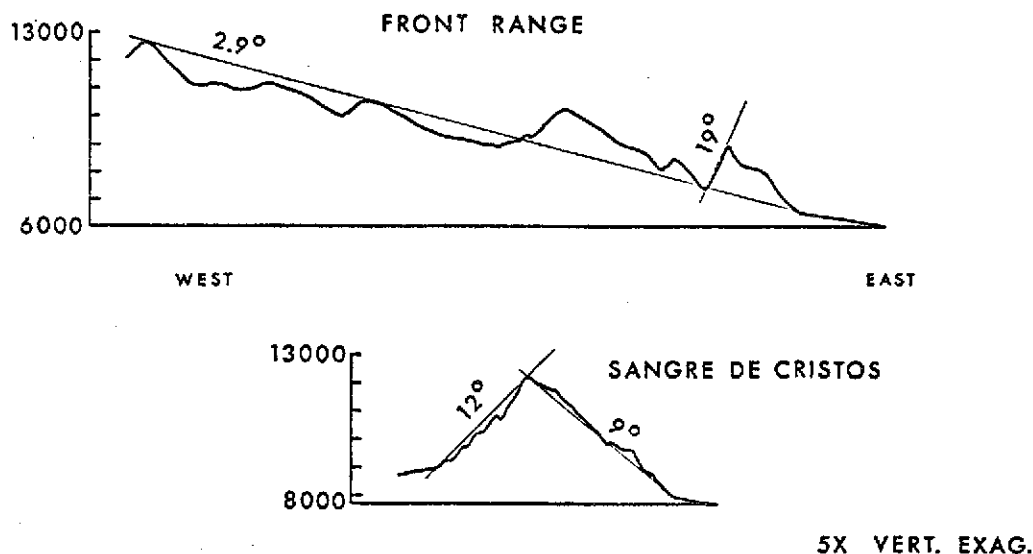
Figure 8: Topographic profiles in Colorado Rockies, with average slope angles. Elevations in feet.

profiles along the Colorado Front Range. The
average slope of the range (east slope), from the
Continental Divide to the edge of the plains, is
2.9°, whereas individual valleys cut into the range
have slope angles commonly 15°-20°. Even the Sangre
de Cristo Range, which is an anomalously steep,
narrow, faulted mountain range, has average slope
angles of 8.8° (east) and 11.8° (west). Thus,
optimum sun angle illumination for space images may
be on the order of 5°-15°. The space image with
the lowest angle illumination available in Colorado
is ERTS imagery with a 20° sun angle, and whereas
this imagery is far superior to high sun-angle
imagery (compare Figs. 9 and 10) for structural
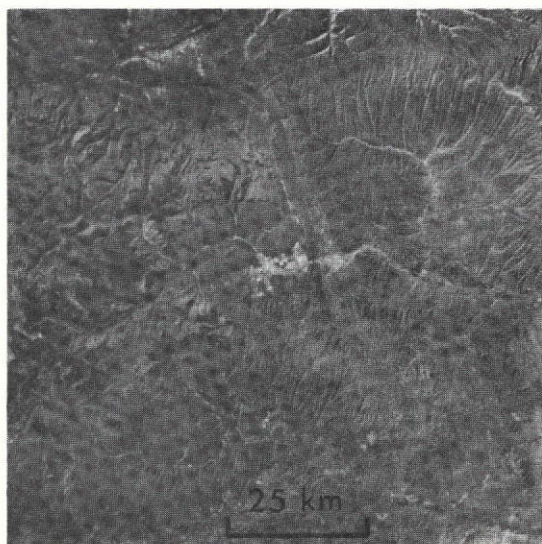
Figure 9: ERTS image
   with 49 degree sun
   angle, 4 Sept 1973.
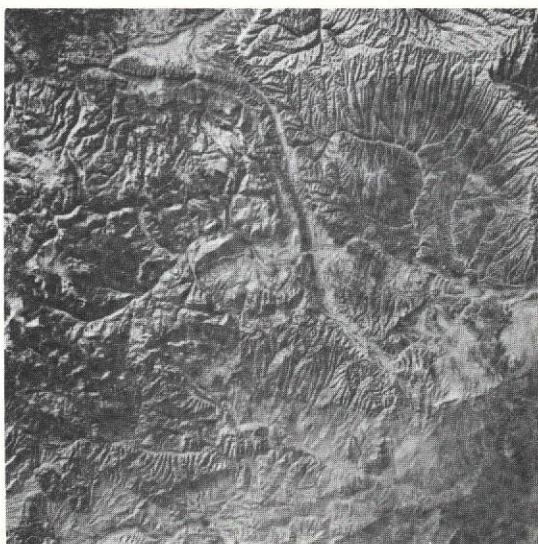
Figure 10: ERTS image
   (same as Fig. 9) with 21
   degree sun angle, 26 Dec
   1972.

studies, it may not be optimum. To this end,
further studies are warranted with, for example,
ERTS imagery taken near the solstices at higher
latitudes.

   Snow cover further enhances imagery with low-
angle illumination (Fig. 11). The contrast between
sunlit and shaded slopes is increased by snow,
especially when the images are acquired with minus-

blue filtration. Under these conditions the
shaded slope is still essentially black (shadow),
whereas the sunlit slope is brighter due to the
increased reflectance of the snow (reflectance of
snow in the photographic region is about four times
that of most rocks and as much as 15 times as great
as coniferous forests). In some cases, snow will
enhance fractures by collecting (or remaining,
during snowmelt) against, along or within topo-
graphic expressions of the fractures. This enhance-
ment is ephemeral, and acquisition of images while
these conditions prevail is largely fortuitous.

Linear topographic lows due to fractures may
also appear on space images as narrow tonal
lineaments. Light tonal lineaments on snow-free
imagery may be caused by alluvium in the valley
bottoms, which generally has a greater reflectance
than bedrock or vegetation on valley walls. On
snow-covered images, light tonal lineaments may
be caused by vegetation-free, snow covered alluvial
flats, as contrasted with forested valley slopes
(Fig. 12,A,B). In arid areas, vegetation

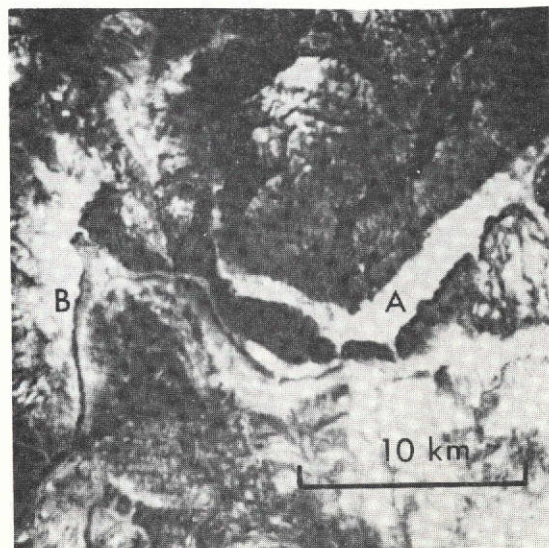Figure 11: Shadow-snow
enhancement of fault-
line scarp. ERTS Band
5.

Figure 12: Snow-covered
alluvial flats, A,B,
contrasted with conifers
on bedrock. ERTS Band 5.

preferentially growing along valley bottoms, where there is more available ground water, may show as dark tonal lineaments (or light lineaments in IR bands).

Tonal lineaments associated with contrasting reflectances of rock units juxtaposed along a fault are rare on space images. The observance of such faults is usually based on other criteria, such as topography or vegetation.

Lineaments are most abundant in crystalline rocks. In large part this may be due to the relatively homogeneous appearance of large masses of crystalline rocks, against which tonal linears tend to stand out, but in part it may reflect the higher natural incidence of fracturing in competent rocks.

In sedimentary rocks, fractures are best seen where their trend is at an angle to the strike of bedding (Fig. 13). Fractures parallel to bedding are often masked by contacts and strike valleys; where they do occur parallel to bedding strike, they are best seen where they occur on dip slopes.

Relatively short, sharply-defined lineaments can be seen on space images. ERTS imagery (red band) studied in one area in southwestern Colorado showed most of the faults longer than 10 km and many of the shorter faults; the shortest fault observed was 3 km long. Skylab S190A photographs (red band) in the same area showed more of the faults than did the ERTS imagery, with the smallest observed fault being 2 km long. Skylab S190B color photographs contain still more fault information; most of the faults in the area were observed except those that occur in closely-spaced sets of parallel faults (that is, individual faults in some fault zones were not observed). The smallest fracture seen was about 1 km long, but probably more significant was that joint spacings of about 200 m were clearly seen (Fig. 14).
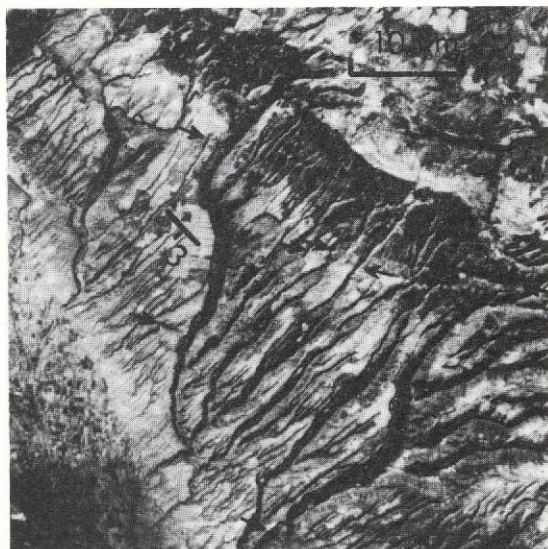
Figure 13: Normal
faults on Dakota sand-
stone dip slope. Arrows
show mapped faults, "?",
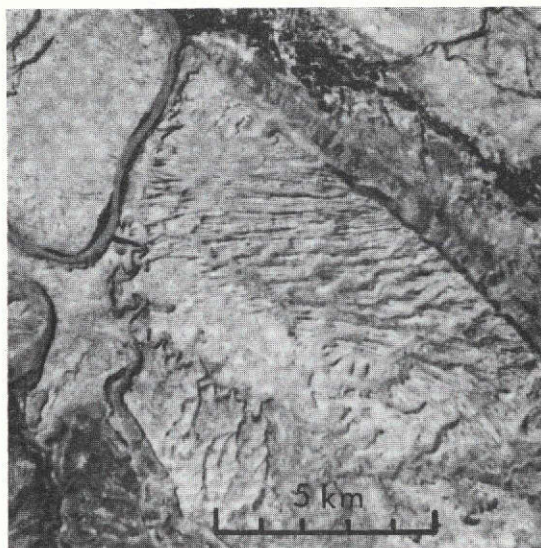possible extensions.
ERTS Band 5.

Figure 14: Joints and
normal faults in Navajo
Sandstone. Skylab S190B
color photo.

High-angle faults are more easily seen than
low-angle faults, because in areas of moderate to
high relief they are expressed as relatively
straight lines, whereas low-angle faults have
irregular fault traces and correspondingly irregu-
lar topographic expression. Long lineaments due
to large faults or shear zones can be traced for
more than 50 km, but many, if not most, of the long
linears that are fairly common on space images
cannot be correlated with known fractures (Fig.
15). By the same token, most of these long linears
cannot be identified as cultural features either,
such as jet contrails (Fig. 16), railroad, roads,
field patterns (Fig. 4,C,D), etc., so they remain
in the realm of speculation. In many cases, we
believe these long linears must be expressions of
geologic structure (perhaps basement faults that
are manifest at the surface only as lines of
weakness) even though they defy identification.
Continued research on the origin of these
lineaments may provide some of the most exciting
geologic results to come from space data.

Figure 15:   Two major lineaments in Colorado Front Range. C, Clear Ck. lineament; E, Empire-Georgetown lineament. ERTS Band 5.
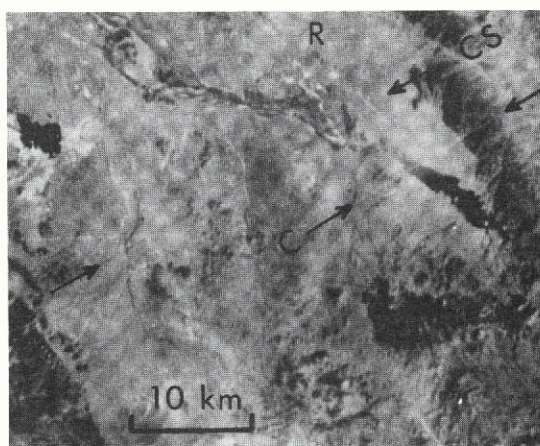
Figure 16:   Linears of non-geologic origin. C, contrail of jet aircraft; CS, shadow of contrail; R, road grid. Skylab S190A photo (red band).

LANDFORMS

Landforms can be recognized on ERTS and Skylab images by the shape or form of the tonal and textural patterns caused by topography and vegetation. Color differences associated with landforms, other than those related to topography and vegetation, are relatively rare, although they do exist.

The capability of detecting and mapping landforms on ERTS and Skylab images is highly variable and depends, in large part, on the imagery contrast between adjacent landforms.

Landforms recognizable on space images fall into three major catagories:

1.   Those associated with relatively recent tectonic activity (faults, folds)
2.   Those associated with recent deposition (alluvium, terraces, talus, glacial deposits, volcanic deposits, etc.)
3.   Those formed by differential erosion of a

> heterogeneous geologic framework (hog-
> backs, fault-line scarps, badlands)

In the geologic interpretation of space images it
is extremely important that landforms be placed in
the proper catagory, since each catagory denotes a
different aspect of the geologic history of an area.

Physiographers rely on large-scale topographic
maps and airphotos for detailed analysis of land-
forms. With ERTS and Skylab images, it is now
possible to study the regional spacial relation-
ships between widely separated landforms and groups
of landforms. In addition, factors affecting the
evolution of landforms, such as geologic structure
and lithology, may be simultaneously evaluated
from the same imagery. The availability of space
images appears to have opened new avenues of
physiographic research.

RECOMMENDED USE OF ERTS AND SKYLAB IMAGES

It has already been suggested that the
approach to interpretation of space images is
basically the same as the approach to geologic
interpretation of aerial photographs. However,
several factors must be considered if maximum use
is to be made of ERTS imagery and Skylab
photography:

1. scale
2. format
3. spectral band
4. conditions of acquisition
5. sensor systems

SCALE

Both ERTS and Skylab images contain more
geologic information than can be interpreted at the
original film scales. Consequently, direct
interpretation of the images 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. Standard ERTS images
(9in x 9in) are at a scale of 1:1,000,000; for
interpretation, ERTS transparencies can be magni-
fied to about 1:250,000 without significant image
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.

FORMAT

As ERTS and 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 re-
quired to map the interpreted information, either
directly onto the enlargements or onto clear
overlays. A good method we have used entails inter-
pretation of low-generation contact positive trans-
parencies under stereo (where available)
magnification, with interpretive results trans-
ferred 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.

The use of stereoscopic viewing cannot be overemphasized. One of the ideas developed in previous sections is that topography is the dominant surface phenomenon used in geologic interpretation of space images, and it obviously follows that stereo viewing is required to use this to optimum advantage. Full stereo coverage (endlap) was obtained by Skylab cameras on many of the EREP passes, and ERTS imagery provides some stereo sidelap (about 35% at Colorado latitudes, providing stereo coverage for about 70% of the ground).

SPECTRAL BANDS

In areas covered by both Skylab and ERTS, the geologist is faced with an array of spectral data from both cameras and multispectral scanners (not to mention thermal infrared and microwave radiometry and spectrometry, which we will not mention). Thus, a few comments are warranted on the choice of spectral bands for interpretation.

Of the ERTS MSS bands, there is no overall "best". Each band has proved best for some geologic feature, under certain conditions. The interrelationships here are complex; suffice it to say that Band 5 (red) has found more use in our area.

Of the Skylab S190A black and white photographs, the red band appears best. Both of the IR bands have very poor resolution, obvious graininess and low contrast. The green band is considerably better, but tends to lack the sharp contrast of the red band. Resolution of the red and green bands appears about the same, but the higher contrast of the red band probably stems from (a) darker shadows due to less red light in shadows, (b) less red light contributed by the atmospheric path, and (c) greater band reflectance differences between vegetation and rock/soil due to the red chlorophyll absorption band.

GEOLOGIC INFORMATION FROM SATELLITE IMAGES

It is possible to produce "true" color and false color composites using the ERTS multiband imagery. In some cases these color composites serve to enhance subtle tonal changes present between lithologic units. The most useful color composite for lithologic mapping appears to be a nearly "true" color rendition made by projecting the green and red bands with green and red light, respectively. However, color composites constructed in this manner using an I^2S color additive viewer are inferior in resolution and general image quality to the individual black and white bands. Color IR composites made by EROS and by General Electric Corp. also appear to be inferior to single band black and white transparencies in resolution and image quality. In short, the use of color additive viewing appears to produce an esthetically more pleasing image at the expense of image quality. As with color photographs, color additive viewing or the purchase of commercial color composites can be an expensive proposition and should be considered only if color additive viewing facilities are readily available or if the actual color of rock units can be used to identify the mapping units. The latter is particularly useful in areas where redbeds are interstratified with light colored (brown, gray, tan, light-green) sedimentary units. In most other types of rock sequences, color composites are of minor usefulness, although other examples could probably be cited.

Color and color IR Skylab photos commonly are better for lithologic discrimination than simultaneously acquired multiband photos (S190A) where changes in rock color are important at lithologic boundaries. However, color photos are more expensive than black and white (multiband) photos, and most geologists on limited budgets must keep this in mind. In addition, lithologic contacts defined by color differences of the rock units are relatively rare in some areas; color differences caused by other factors (e.g. - vegetation, topographic effects) may be equally detectable and mappable on black and white photos. Color photos

are no better than black and white photos in snow-covered scenes.

CONDITIONS OF ACQUISITION

The consideration of time of day and time of year that space data are acquired may be extremely important. The former can be translated directly to solar elevation, or the incidence angle of scene illumination; the latter may involve both illumination angle and azimuth, as well as snow cover and different stages of plant growth.

As was pointed out in previous sections, topography, and thus geology, may be more easily interpreted when illuminated at low elevation angles. Not only are many subtle features enhanced, but some features (notably high-angle linear slopes) are selectively enhanced as a function of their orientation (Sawatzky and Lee, this publ.). The optimum sun angle obviously is a function of relief, and cannot be defined here without more study, but we suggest that, for areas like the Rocky Mountains, approximately 10° may be best.

For a given sun angle, azimuth will vary seasonally. For a given time of day, both azimuth and sun angle will also vary seasonally. In the case of the ERTS satellite, with its fixed time of overpass, obtaining imagery from different times of the year is the only way to vary sun angle. During the study of structures in NW Colorado (shown in Fig. 18), initial interpretation of ERTS imagery taken with a 42 degree sun angle revealed 10 folds; the final interpretation of 63 folds was made on ERTS imagery with a sun angle of 21 degrees.

The use of winter images in Colorado must contend with nearly-complete snow cover. The effect of the snow is mixed; it tends to obscure differences in rock reflectance, but it may enhance topographic and forest/non-forest contrasts. Snow probably hinders more than helps lithologic

discrimination, and is, overall, most beneficial for structural interpretations

As discussed under Lithology, the maximum amount of geologic information can be obtained by using as many images as possible, acquired under as many different conditions as possible. This has obvious practical limitations, but we think obtaining at least early summer and early winter images is worthwhile. The consideration of time of year is generally of lesser importance for Skylab photos than for ERTS images, simply because the number of Skylab data passes over a given area was limited - commonly to one.

SENSOR SYSTEMS

The advantages and disadvantages of the sensors aboard the ERTS and Skylab satellites should be considered. For practical use of space data by professional geologists, we are discussing imaging systems only; the use of non-imaging systems is restricted at present to research-oriented groups.

The ERTS imaging system (MSS) has several advantages compared to Skylab:

1. Coverage over nearly the entire earth's surface is possible. Coverage right now is complete over the United States, so any area of interest has imagery available. The coverage by Skylab is very limited, and photography of a given area may well not exist.
2. Coverage by the ERTS satellite is repetitive. This characteristic offers not only the capability for studying time-variant phenomena, but a greater probability of obtaining images under near-optimum conditions. The limited opportunities of Skylab precluded acquisition of cloud-free photographs over even some of the priority target areas.

3. ERTS images are generally available at lower sun angles than Skylab photos (though perhaps not low enough). Even though Skylab photos could theoretically be acquired at optimally low sun angles, they in fact were not.

4. ERTS data are suited to automatic processing, whereas Skylab photographs are not. For geologic purposes, however, this apparent advantage is more theoretical than real, since, to date, no practical advantage of this capability has been demonstrated. (Skylab's S192 multispectral scanner data have not yet been properly evaluated.)

The Skylab camera systems have several advantages compared to ERTS:

1. The resolution of Skylab cameras is far superior to the resolution of the ERTS scanner, providing far more scene detail. This is particularly true of the S190B camera, with its 18-inch focal length.

2. Both Skylab camera systems provided color photographs, obviating the need for color-additive viewers or color reconstitution, with their attendant degradation.

3. Full stereo coverage is possible along the ground track, although sufficient endlap was not always acquired.

4. Not only could Skylab obtain photography with optimally low sun angle, but the whole range of southwest illumination azimuths was available.

A distillation of the above comparisons would suggest that advantage should be taken of both systems, where possible, under as many different conditions as possible. Where good, cloud-free, S190B color photography with full endlap stereo is available, it will provide the most geologic information.

GEOLOGIC INFORMATION FROM SATELLITE IMAGES

APPLICATIONS OF SPACE DATA

Images from ERTS and Skylab are merely
interesting curiosities unless skillful, enter-
prising geoscientists extract and use the basic
geologic information in the data. In this respect,
space data are not different from aircraft
photography; only the scale and detail of the
available information are more regional in scope.

Prior to the acquisition of space data, great
effort was made to produce mosaics covering large
areas to get the regional overview. Often this
was the only way to obtain an understanding of the
regional geologic framework. Mosaics were used
during the initial stages of geologic investigation
to pinpoint areas of interest, and later were used
to check, extend, and correlate geologic informa-
tion from field studies. Space images serve this
purpose even better.

ERTS and Skylab images exist over many parts
of the world for which aircraft photography does
not exist and, hence, are the only available images.
They can be effectively applied to many geologic
problems, and they become even more powerful when
combined with aircraft photography and field
investigations. Some examples of the broad
applications of space images are discussed below.

TECTONIC ANALYSIS

ERTS and Skylab images provide a tool by which
the geoscientist can probe into the tectonic
evolution of large regions of the earth's crust.
Tectonic analysis may utilize geologic maps
constructed from space images or it may involve
specially-prepared maps showing only the major
structures of a region. In either case, tectonic
analysis may be geared toward more specialized
problems, such as mineral or petroleum exploration.

A good example of tectonic analysis using
ERTS imagery is the work of Dr. R.J. Weimer of the

Colorado School of Mines (CSM) in the area of the
Raton Basin of south-central Colorado (Fig. 17).
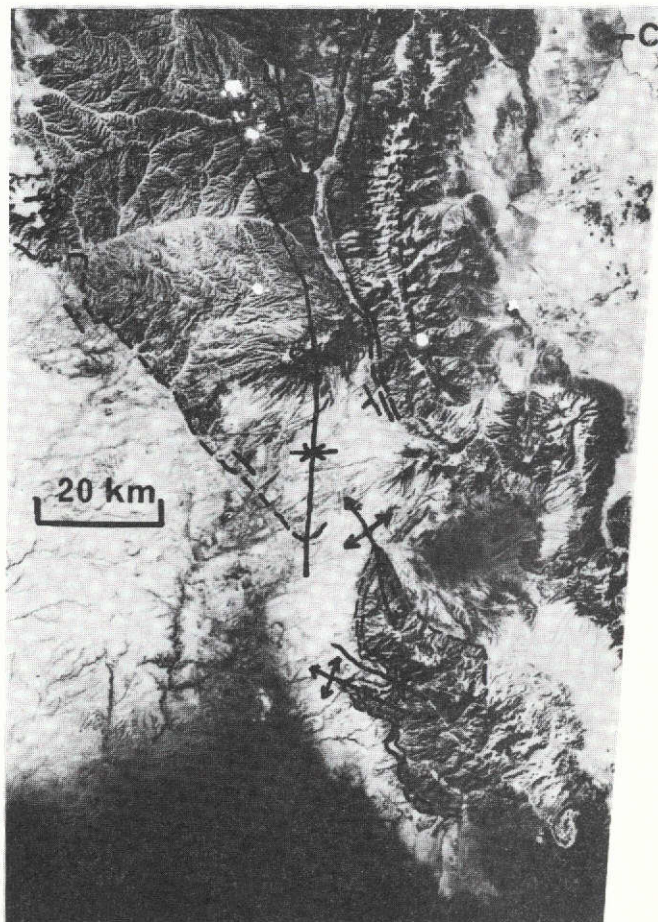

Figure 17: ERTS image 1189-17091 of the Raton
  basin area of south-central Colorado. Major
  lithologic contacts and structures are shown. S,
  intrusive body at Spanish Peaks with radiating
  dike swarm; C, cinder cone in the San Luis Valley;
  F, basaltic lava flows of Raton Mesa; A, anti-
  cline.

On the ERTS image, certain key lithologic units
were mapped to show the basin and mountain-flank
structures in the area. A stratigraphic section
was developed that could be traced throughout the
area. The intrabasinal anticline (a possible oil
trap) found on the imagery (Fig. 17,A) is one

example of the potential of tectonic analysis of ERTS imagery for petroleum exploration. This structure has been drilled, but it is not a producer.

Intrusive igneous rocks have invaded the sedimentary rocks at S, and numerous radiating dikes can be seen associated with the intrusive bodies. From this relatively simple tectonic map, a sequence of geologic events can be interpreted.

1. Basining and sedimentation
2. Folding
3. Intrusion
4. Erosion

Although this analysis did not produce much "new information" in this area because many ground investigations had already been conducted, this same type of analysis would be valuable in less well-known part of the world. However, the potential of discovering new tectonic relationships even in relatively well-known areas exists because of the regional overview provided by ERTS and Skylab images. It is in the capability of discovering "new information" and the isolation of critical areas for more detailed geologic study that the real worth of space images will ultimately be measured.

PETROLEUM EXPLORATION

Today the search for petroleum has attained a premier position. Geologic studies of ERTS imagery of northwestern Colorado by Dr. D.W. Trexler of Colorado School of Mines (reported in Knepper, 1973) suggests that space images may be useful tools in exploring for new petroleum reserves.

ERTS imagery of a highly petroliferous area of northwestern Colorado (Fig. 18) was studied to determine if numerous folds in the area could be mapped. The troughlines and crestlines of 63 folds were mapped and most of these correlate with known
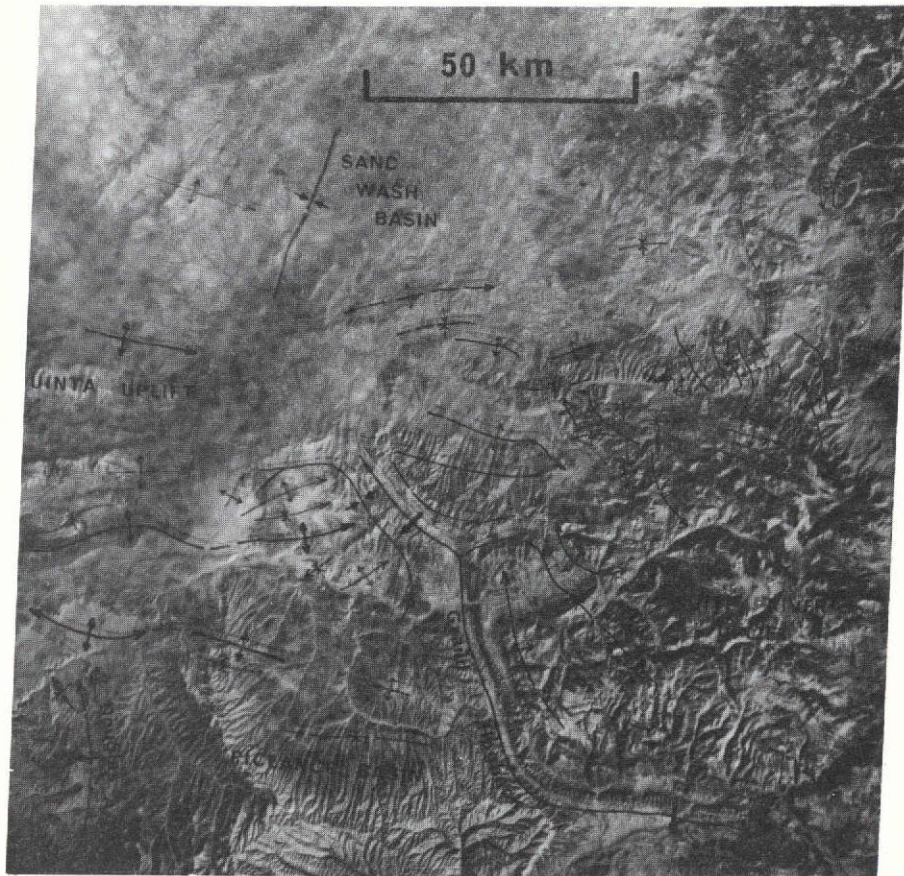
Figure 18: ERTS image 1156-17253-7 of northwestern
  Colorado showing major folds of the region.
  Structural symbols displaced slightly so as not
  to obscure image expression (shadows of symbols
  at proper location).

folds in the area, several of which are producing
or have produced oil. Several folds were mapped
on the ERTS imagery that do not correlate with
known folds in the area. These "new" folds have
not been verified in the field, but the good
correlation of the other ERTS-mapped folds with
known structures suggests that the "new" folds
are surely worthy of more study. The fact that
potential structural traps can be mapped on ERTS
imagery indicates that the use of ERTS or Skylab
images will increase the efficiency of oil explora-
tion in other parts of the world.

MINERAL EXPLORATION

Linear patterns suggesting fractures or fracture zones (lineaments) are commonly the most abundant geologic information that can be extracted easily from ERTS and Skylab images. Analysis of these lineaments can take a variety of directions, depending on the specific geologic problem that is being investigated. One of the more interesting and potentially useful methods of applying this type of fracture information was demonstrated by S.M. Nicolais at the Third ERTS-1 Principal Investigator's Symposium. The study showed that analysis of specific lineament patterns, combined with frequency of intersections, can be a fairly reliable guide to areas of metallic mineralization in central Colorado. The method and results of this investigation are briefly summarized below--see Nicolais (1973) and Knepper (1973) for detailed discussions.

Well-defined lineaments, poorly- to moderately-expressed lineaments, and circular or strongly curved lineaments were mapped on a 1:1,000,000 positive transparency of an ERTS image of central Colorado (Fig. 19A,B). Under the assumptions that metallic mineralization is controlled by fractures and shear zones, and that mineralization is usually associated with intrusive and volcanic centers, 10 circular areas of 14 km diameter were chosen as potential sites of metallic mineralization (Fig. 19B). Priorities were assigned to each of the 10 target areas based on 1) frequency of lineament intersections and 2) types of lineaments. Areas of high density of lineament intersections, associated with circular lineaments suggestive of intrusive or volcanic centers, were considered the most promising areas for exploration.
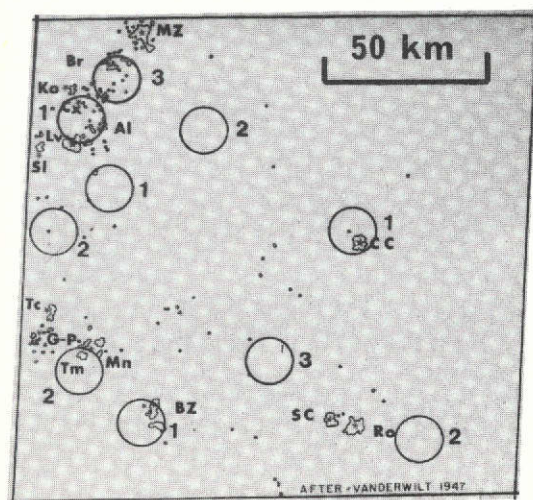
The target areas picked from the ERTS lineament map were compared to the known mineral producing areas of the ERTS image (Fig. 19C). Five of the ten target areas together included the Breckenridge, Leadville-Climax-Alma, Tomichi, Bonanza, and Cripple Creek mining districts, which

A. ERTS image
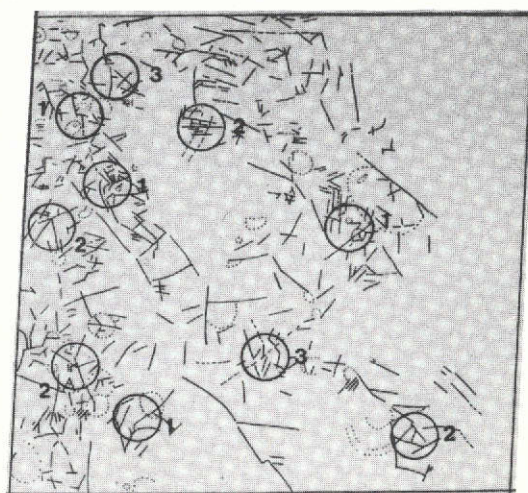
B. Lineament map.

C. Mineral districts

MZ-	Montezuma
Br-	Breckenridge
Ko-	Kokomo
Cx-	Climax
Al-	Alma
Lv-	Leadville
SL-	Sugarloaf
Tc-	Tincup
G-P-	Goldbrick-Pitkin
Mn-	Monarch
Tm-	Tomichi
BZ-	Bonanza
SC-	Silver Cliff
Ro-	Rosita
CC-	Cripple Creek

Figure 19: ERTS imagery applied to metallic mineral exploration in central Colorado. Numbered circles are target area selections and their priority (1, highest, etc.). Irregular, starred areas are major mineral districts; small dots are areas of minor production.

have a combined metallic mineral production of
$2,438,328,722 (Marsh and Queen, 1973). Even more
significantly, three of the four target areas given
the highest priority rating included the Leadville-
Climax-Alma, Bonanza and Cripple Creek mining
districts, which together have produced
$2,374,399,283, or 97% of the total mineral pro-
duction within the areas outlined by the 10
original target areas.

Because these results were much better than
had been anticipated, it was suspected that the
photo-interpreter's prior knowledge of the location
of many of the mineral districts may have unduly
biased his original 10 target area selections. To
check this, mis-oriented copies of the lineament
overlay (only) were distributed to 15 geology
professors and graduate students at the Colorado
School of Mines. Each member of the group was
asked to outline 10 circular target areas of
14 km diameter that they believed held potential
for metallic mineralization. The results of the
test group's selections are shown in Table 1.

Without knowing where the test area was or
having the benefit of the ERTS image to study, a
large percentage of the test group chose the same
target areas as did the original photo-interpreter.
This indicates that prior geologic knowledge had
little influence on the selection of the original
ten target areas and increases the credibility of
using ERTS photo-lineament information as a guide
to mineral exploration.

Since the structural control and intrusive
and volcanic associations of metallic mineral
deposits are not unique to central Colorado, this
technique should be applicable to less well known
regions of the world. The real application of this
technique is not to directly find mineralization
from ERTS or Skylab images, but to restrict the
areas of search to primary target areas that would
have to be studied in more detail, both from

aircraft photography and in the field. To this
end, the technique appears to be very effective.

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

Table 1. Test group results. Each letter across
the top corresponds to a member of the test group.
X's identify mineral districts included in target
area selections; O's identify mineral districts
included in original target area selections. The
last column shows the percent of group selecting
each mineral district.

SUMMARY

We have discussed briefly several geologic
applications for which ERTS and Skylab images can
be used--many more can be imagined. However, the
geologic applications of space images will be
largely limited to problems for which regional
geologic relationships and the general geology of
large areas must be determined. Furthermore, there
are but a few types of geologic problems for which
analysis of ERTS or Skylab images will produce
the ultimate solution; more commonly, detailed
studies of selected areas by aircraft photography
and ground investigations will be necessary to

provide the final answers. In areas of the world where the geology is not well known, particularly in the underdeveloped countries, ERTS and Skylab images may be applied with a high probability of producing beneficial new information. Even in relatively well-known areas, such as the continental U.S., new information may be found on space images, but finding it will be more difficult.

We have shown some examples where the extraction and analysis of basic geologic information derived from ERTS and Skylab can be applied to specific geologic problems. Further applications will be developed by innovative geoscientists capable of treating this new type of geologic information. At this stage, therefore, it is difficult to place firm limits on the applicability of ERTS and Skylab images to geologic studies-- the avenues to potential applications have barely been opened.

CONCLUSIONS

1. Satellite images contain the same geologic information as do conventional aerial photographs - basically lithology, structure, and landforms.

2. The fundamental differences between satellite images and aircraft aerial photographs are scale and resolution. The main effect of smaller scale is to portray regional geologic features in a new, synoptic perspective; poorer ground resolution tends to smooth out (average) minor variations.

3. As with conventional air photos, the geologic interpretation of space images is based on deduction from surface phenomena. Topography is the single most important surface expression interpreted.

4. In the deductive interpretation, the geologist-interpreter is necessary.

5. Skylab S190B color photography, where available, provides more geologic information than any other single satellite sensor. Maximum geologic information is derived from images of different sensors acquired under differing conditions.

6. More geologic information is contained in space images than can be interpreted or mapped at original scales. Interpretation should be conducted under magnification of low-generation contact transparencies and mapping carried out on enlarged prints or transparencies.

7. All interpretations of space images must be verified by field checking, perhaps more so than interpretations of air photos, due to our lack of familiarity with these new forms of data.

8. Maximum geologic information will be extracted through an iterative process of image interpretation and field checking.

9. Space images are an excellent buy for geologists. NASA has already acquired them, and the only cost to the user is for copies.

ACKNOWLEDGMENTS

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