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DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

INTEGRATION OF GEOLOGICAL REMOTE SENSING TECHNIQUES IN SUBSURFACE ANALYSIS

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TECHNIQUES IN SUBSURFACE ANALYSIS

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ABSTRACT

Geological remote sensing is defined as the study of the Earth utilizing electromagnetic radiation which is either reflected or emitted from its surface in wavelengths ranging from 0.3 micrometre to 3 metres. The natural surface of the Earth is composed of a diversified combination of surface cover types, and geologists must understand the characteristics of surface cover types to successfully evaluate remotely-sensed data. In some areas landscape surface cover changes throughout the year, and analysis of imagery acquired at different times of year can yield additional geological information. Integration of different scales of analysis allows landscape features to be effectively interpreted. Interpretation of the static elements displayed on imagery is referred to as an image interpretation. Image interpretation is dependent upon: (1) the geologist's understanding of the fundamental aspects of image formation, and (2) his ability to detect, delineate, and classify image radiometric data; recognize radiometric patterns; and identify landscape surface characteristics as expressed on imagery. A geologic interpretation integrates surface characteristics of the landscape with subsurface geologic relationships. Development of a geologic interpretation from imagery is dependent upon: (1) the

geologist's ability to interpret geomorphic processes from their static surface expression as landscape characteristics on imagery, (2) his ability to conceptualize the dynamic processes responsible for the evolution of interpreted geologic relationships (his ability to develop geologic models). The integration of geologic remote-sensing techniques in subsurface analysis is illustrated by development of an exploration model for ground water in the Tucson area of Arizona, and by the development of an exploration model for mineralization in southwest Idaho.

INTRODUCTION

Geological remote sensing techniques are employed to minimize costs and maximize results of ground-based geologic investigations. Prediction of subsurface geological relationships from analysis of remotely sensed data is dependent upon the expertise of the data analyst who evaluates variations in electromagnetic energy emanating from the Earth's surface and extrapolates to the subsurface using these surficial attributes and predictive, conceptual geologic models.

Definition of geological remote sensing.--Geological remote sensing can be defined as the study of the Earth utilizing electromagnetic radiation (EMR) which is either reflected or emitted from the land surface in wavelengths ranging from ultraviolet (0.3 micrometre) to microwave (3 metre). The geological remote-sensing spectrum thus includes only a portion of the entire electromagnetic spectrum (figure 1). In contrast, geophysical remote sensing can be defined as the study of the Earth using electromagnetic radiation of wavelengths shorter than ultraviolet (x-rays, gamma rays) and longer than microwave (radio). Some scientists include magnetic, gravity, sonic, and seismic methods as geophysical remote-sensing techniques, but these methods do not detect electromagnetic radiation.

ELECTROMAGNETIC ENERGY AND THE EARTH

Electromagnetic radiation is radiant energy in wave and particulate form that is propagated through space at the speed of light. It is classified according to the number of wavecrests which pass an arbitrary point each second (frequency) or according to the distance between wavecrests (wavelength).

ELECTROMAGNETIC ENERGY SPECTRUM

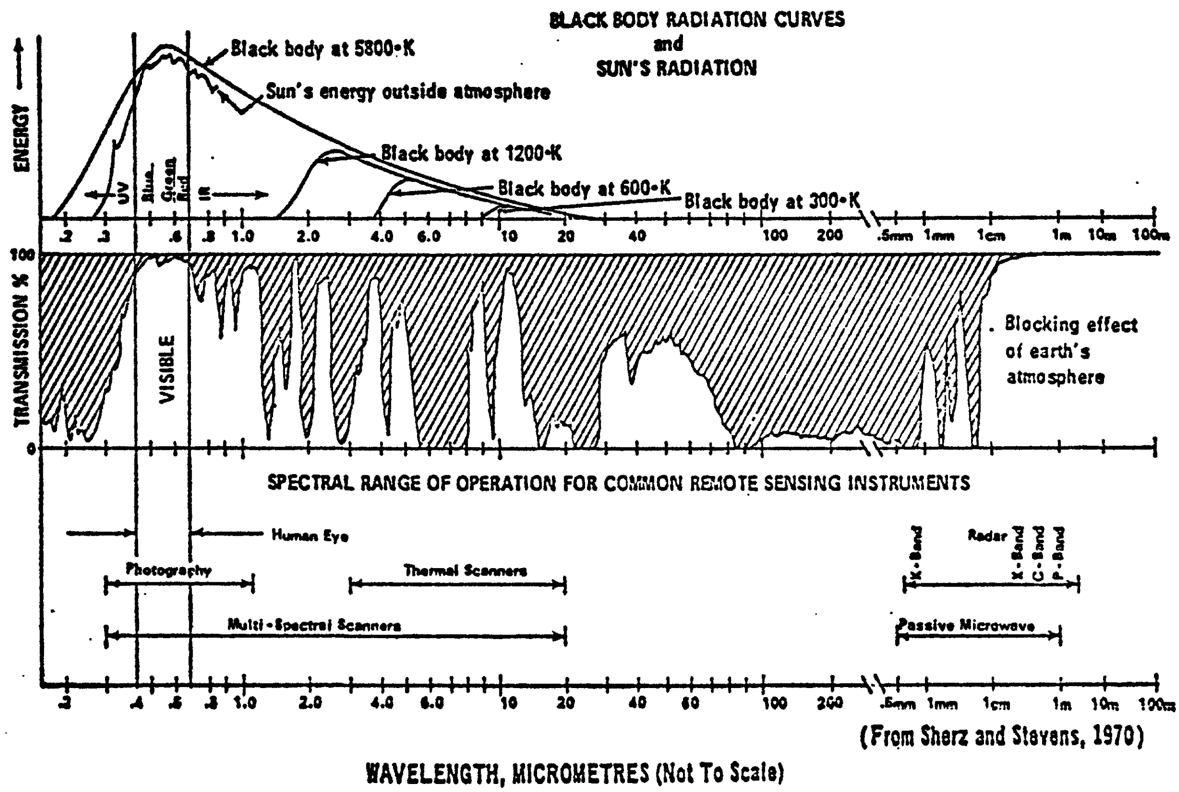


Figure 1: Electromagnetic energy spectrum.

Electromagnetic radiation originates in the Sun, in the Earth, or can be generated by artificial sources. The Sun's spectral energy distribution has a maximum at a wavelength of 0.5 micrometre (a wavelength close to the peak sensitivity of our eyes). Solar radiation is largely unaffected as it travels through space, but is selectively scattered and absorbed by the Earth's atmosphere. The atmosphere scatters blue wavelengths of visible light four times more than red wavelengths. The Earth's surface is illuminated by EMR from the Sun (figure 2) that is not scattered or absorbed by the atmosphere

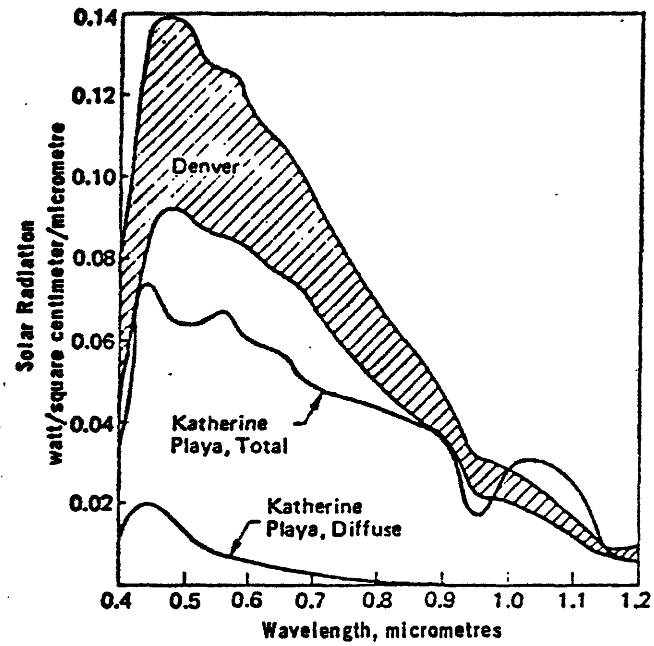


Figure 2: Variations in solar incident radiation between 0940 and 1430 hours in the spring near Denver, Colorado (shaded). Upper curve is for 1430 hours. The curve for Katherine Playa, New Mexico shows total solar radiation (daylight) for a typical clear winter day in a dry atmosphere. The skylight curve for Katherine Playa is typical for the scattered (diffuse) part of solar radiation. From NASA Skylab Earth Resources Data Catalogue, Johnson Space Center, Houston, Texas, 1974.

(sunlight), and by atmospherically scattered solar EMR (skylight). The dominant spectral component of sunlight is yellow, whereas that of skylight is blue. Sunlight and skylight (daylight) combine to produce white light that has spectral characteristics which change throughout the day. Because the Sun's radiation must travel through a longer atmospheric path at sunrise and sunset, the atmospheric scattering causes the Sun to appear more red and the sky overhead to appear more blue at those times of the day. Scattered blue skylight illuminates topography that is not directly illuminated by the Sun (topography in shadow).

Electromagnetic radiation from the Sun that is incident upon the Earth's surface is absorbed, reflected, and in some cases, transmitted through materials. Natural EMR emitted by the Earth's surface comes mostly from solar energy absorbed in the visible and near-visible portions of the electromagnetic spectrum (EMS), and secondarily from local geothermal sources (such as volcanoes and hot springs). Electromagnetic energy is also radiated through the Earth's skin as heat is conducted from the Earth's hot interior, but this amount of thermal EMR is small compared to that furnished by the Sun. Absorbed solar energy is mostly reradiated from the Earth's surface in the thermal (3 to 5 micrometre) portion of the EMS. Except for geothermal areas, variations in the Earth's surface temperature are mostly related to the angle at which the Sun's radiation strikes the Earth's surface and the manner in which this energy is absorbed and reradiated by earth materials.

The process of "reflection" takes place within one-half wavelength of a material's surface, in the molecular structure of the material, and results in the instantaneous reradiation of EMR. The amount of EMR reflected from the Earth's surficial materials depends on the spectral distribution and intensity of incident energy, the angle of incidence of incoming radiation, the orientation of topography, the roughness of the topographic surface with respect to incident radiation, and the absorptive characteristics of the materials.

Specular (mirror) reflection occurs when incident EMR strikes a surface with irregularities (roughness) of dimensions many times smaller than the wavelengths of incident EMR. If a surface has irregularities of dimensions close to or larger than those of the wavelengths of incident EMR, diffuse (hemispherical) reflection may occur. At visible and near-visible wavelengths most natural surfaces behave as mixed reflectors and have the properties of both specular and diffuse reflectors. On horizontal surfaces some incident EMR is scattered forward, away from the direction of illumination, and some incident EMR is scattered back in the direction of illumination; the forward scatter is dominant for most natural materials. The amount of EMR reflected to a remote sensing system is related to the orientation of small (with respect to incident wavelengths) specular reflection surfaces, the angle of incident radiation, and the angle of observation. Consider a relatively flat, granite outcrop. Most of the individual reflecting surfaces may lie almost horizontally, some may dip gently away from or toward the source of illumination, and a few may face directly away from or toward the source of illumination. The distribution of reflected radiation from small surfaces oriented in this manner is shown in figure 3. The longest vector represents energy that is specularly reflected from the almost horizontal surface.

DETECTION OF ELECTROMAGNETIC RADIATION

The most commonly used geological remote-sensing tools only detect EMR that is emanating from the upper millimetre of the Earth's surface (figure 4), and, except for snow, ice, clear water, grass blades, brush, leaves on trees, and very dry materials in deserts, there is almost no

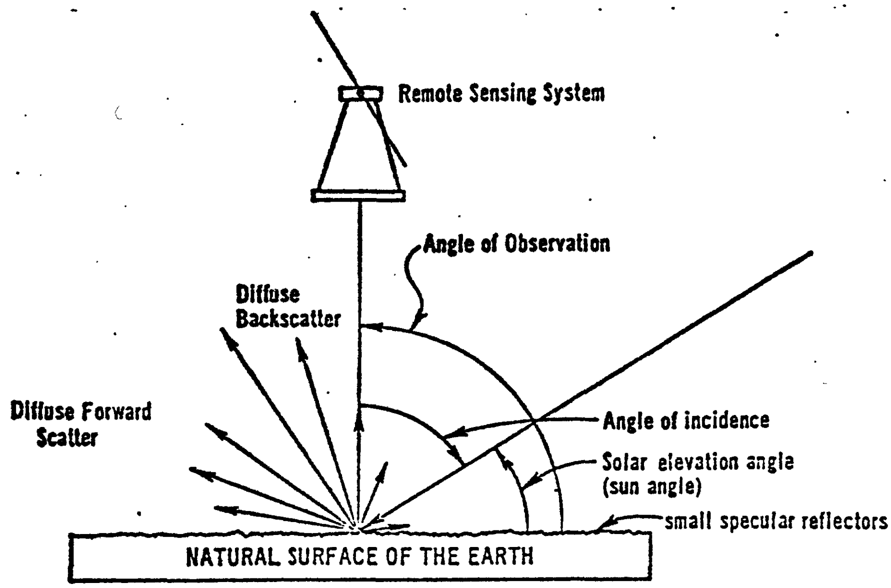


Figure 3: Reflection of incident solar radiation from natural surfaces

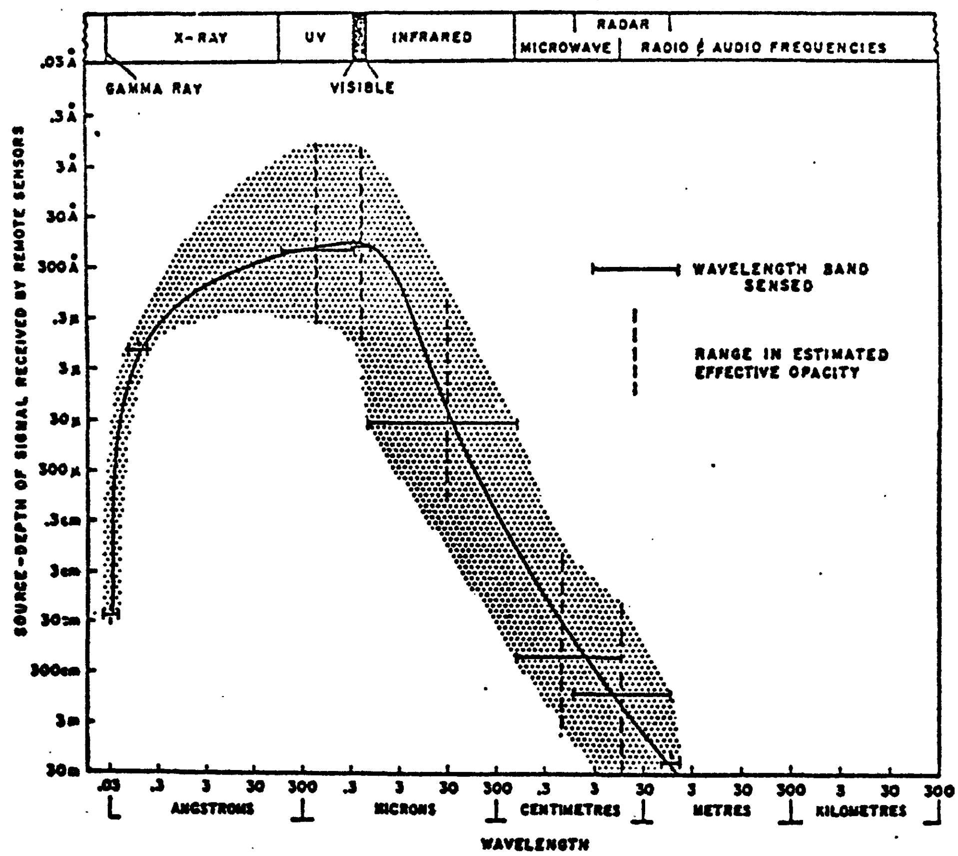


Fig. 4 Generalized absorption-coefficient curve for dry natural materials derived from terrestrial data; indicates estimated source-depth of information in received signal expected from lunar surface materials. In part after Badgley and Lyon, 1964, N.Y. Acad. Sci., and Second Symposium on Remote Sensing of Environment, October 15-17, 1962, U. of Michigan.

transmission of EMR through earth materials. In the visible and near-visible portions of the electromagnetic spectrum remote sensors detect reflected radiation; whereas, the Earth is the source of passive EMR detected in the thermal infrared through the microwave (3.0 micrometre) to 3 metre) portion of the electromagnetic spectrum.

Active microwave (radar) systems produce their own EMR which is transmitted from an antenna toward the Earth's surface at an angle less than 90 degrees. Radar EMR is scattered, absorbed, and reflected back to a receiving antenna, the returns depending on the angle of incidence, orientation of topography relative to the transmitter, surface roughness, and the electrical properties of the earth materials present.

The radiation type, wavelength, frequency, usual source, and the usual methods of detection of the EMS are summarized in table 1. Units commonly used in geological remote sensing are summarized in table 2.

Material responses.--Remote detection of a spectrum of different EMR wavelengths emanating from the Earth's surface allows different properties of earth materials to be evaluated (figure 5). Representative visible and near-visible spectral characteristics of natural surficial materials are summarized in figures 6, 7, 8, 9, and 10.

Topographic responses.--The topographic arrangement of the Earth's surface can have a significant affect on the amount of electromagnetic radiation reflected and absorbed by it, especially when incoming, illuminating radiation does not strike the surface at right angles. Consider a ridge illuminated by solar radiation. If the ridge is along the ground track of the Sun, both sides of the ridge will be equally

TABLE 1

The Electromagnetic Spectrum for Geologic Remote Sensing

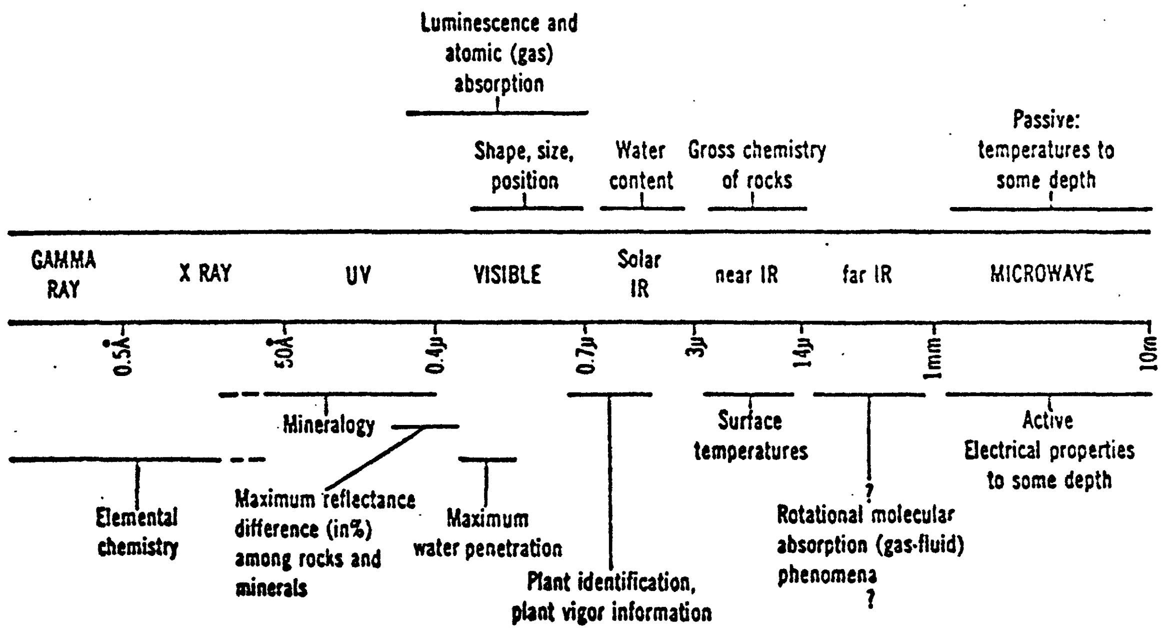
KINDS OF WAVES	WAVELENGTH (cm)	FREQUENCY (Hz)	USUAL SOURCE	USUAL METHOD OF DETECTION
Ultraviolet	$3\text{-}4 \times 10^{-5}$		Disturbance of intermediate electrons	Fluorescence chemical effect
		$f = \frac{c}{\lambda}$		
Visible		$c = 3 \times 10^{10}$ cm/sec.	Disturbance of valence electrons	Eye, photo-chemical effect, photo-detectors
Blue	$4\text{-}5 \times 10^{-5}$			
Green	5-6 "			
Red	6-7 "			
Infrared			Disturbance of atoms and molecules. Vibration and rotation molecular motion	Photo-chemical effect for near visible, semi-conductor detector
Near (photo)	$0.7\text{-}1.5 \times 10^{-4}$			
Thermal				
(1)	3.5-5.5 "			
(2)	8.0-14 "			
Microwave			Molecular motion. Electrical resonance of tuned circuits antenna	Diodes, solid state crystals, antenna
Passive (Thermal)	0.05-100	600-.3 GHz		
Active (Radar)	0.10-300	300-.1 GHz		

TABLE 2

Units Commonly Used in Geological Remote Sensing

UNIT	USE (Abb.)	RELATIONSHIP TO OTHER UNITS
Wavelength		Metres
Nanometre	Standard Unit (nm)	10^{-9} metre
Micrometre	Standard Unit (μm)	10^{-6} metre
Centimetre	Standard Unit (cm)	10^{-2} metre
Metre	Standard Unit (m)	metre
(Angstrom)	By physicists in Gamma Ray, X-ray, and Visible (Å)	10^{-10} metre
(Millimicron)	By physicists, and electrical engineers (mμ) in visible. Discont.	10^{-9} metre
(Micron)	By physicists, and electrical engineers (μ) in thermal infrared use discontinued	10^{-6} metre
Frequency		Cycles per second 1 cps = 1 Hertz
(Picohertz)	Standard Unit (PHz)	10^{10} cps
Gigahertz	Standard Unit (GHz)	10^{9} cps
Megahertz	Standard Unit (MHz)	10^{6} cps
Kilohertz	Standard Unit (KHz)	10^{3} cps
Hertz	Standard Unit (Hz)	1 cps
Photometric and Radiometric Quantities		
Radiance	Used in reference to the amount of electromagnetic energy received, reflected, or emitted.	Watts per cm^2
Radiant spectral emittance	Used in reference to the amount of energy emitted over a definite wavelength interval	Watts per cm^2 per micrometer

FIGURE 5: Summary of types of information and/or properties of materials that may be interpreted from observations of various parts of the electromagnetic spectrum



IDEALIZED CURVES SHOWING RELATIVE REFLECTANCE OR BACKSCATTER FROM COVER TYPES

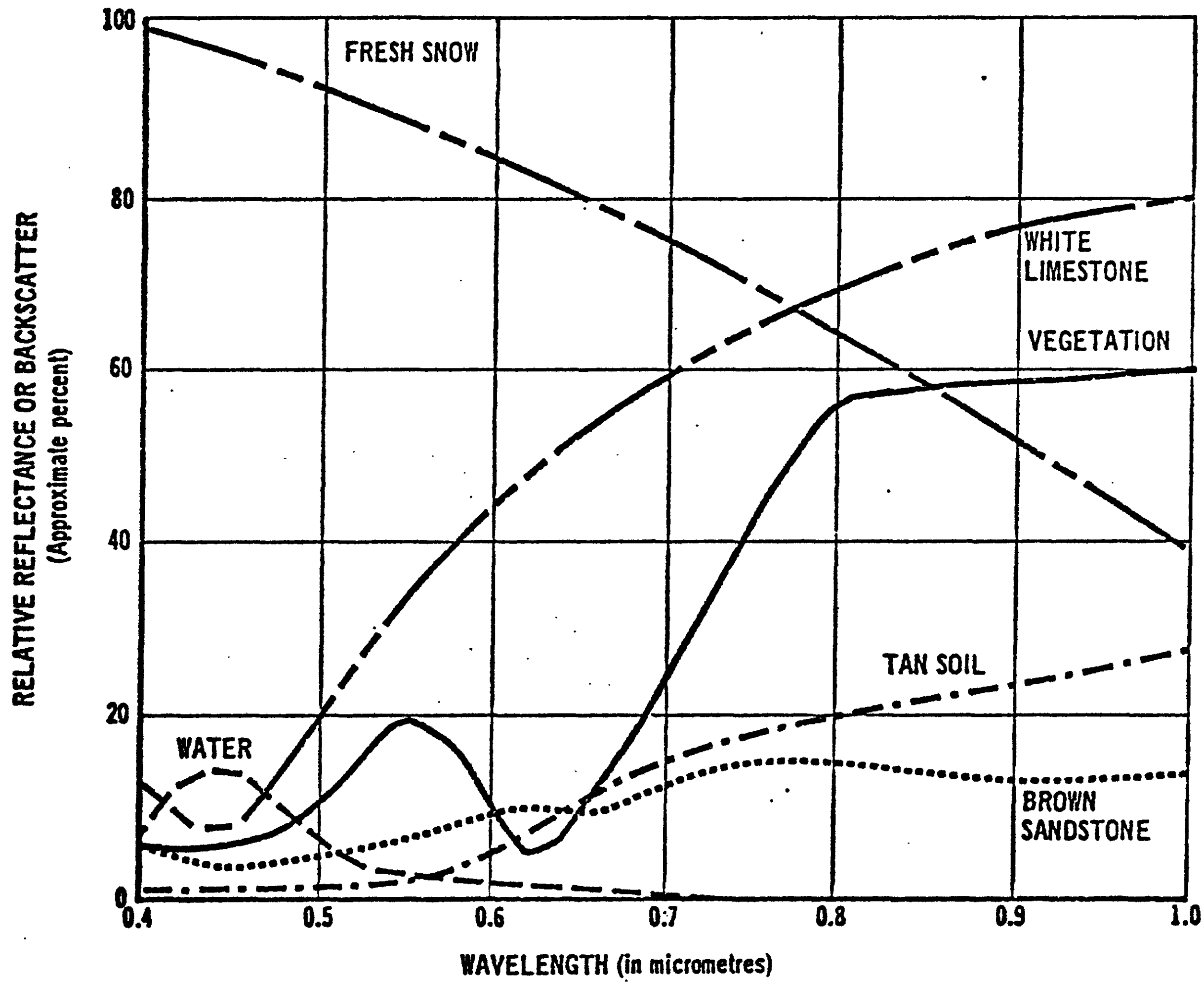


FIGURE 6: General spectral characteristics of main cover types
Some data from G. Moore, personal communication

IDEALIZED CURVES SHOWING RELATIVE REFLECTANCE OR BACKSCATTER FROM COVER TYPES

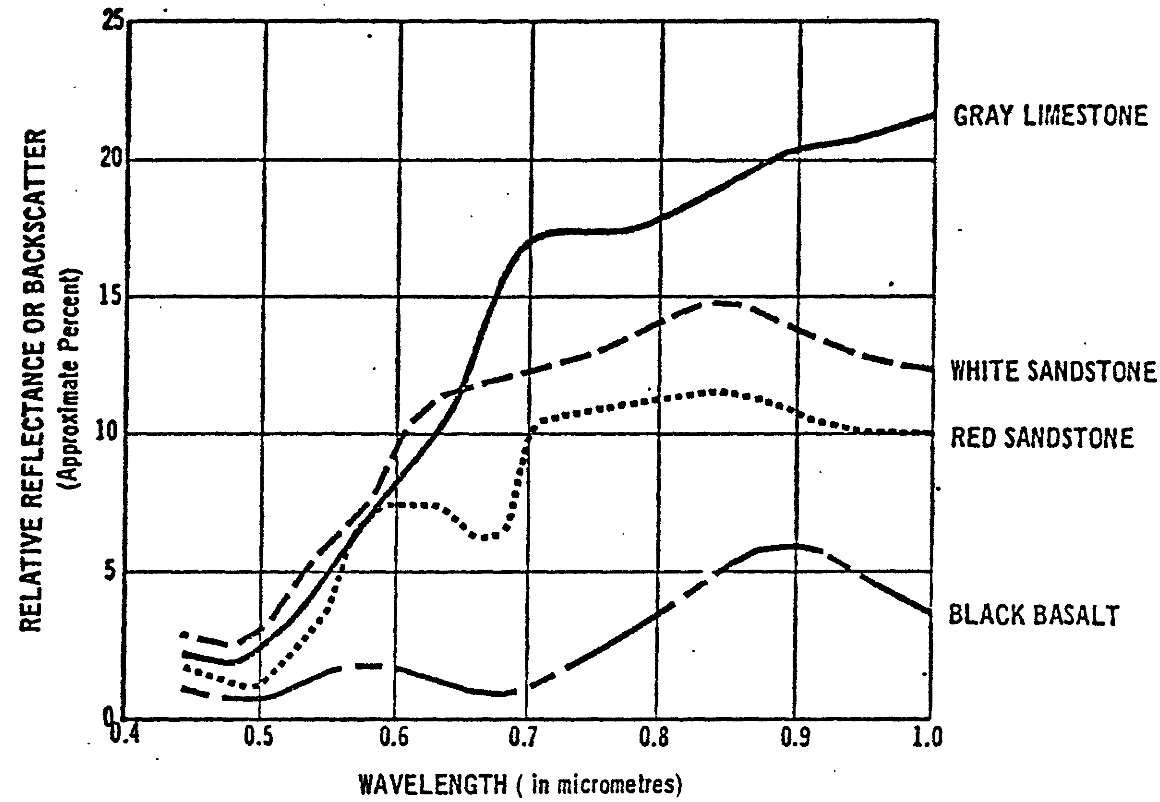


FIGURE 7: Spectral characteristics of rock types. Data in unpublished form furnished by Orr and from visual analysis

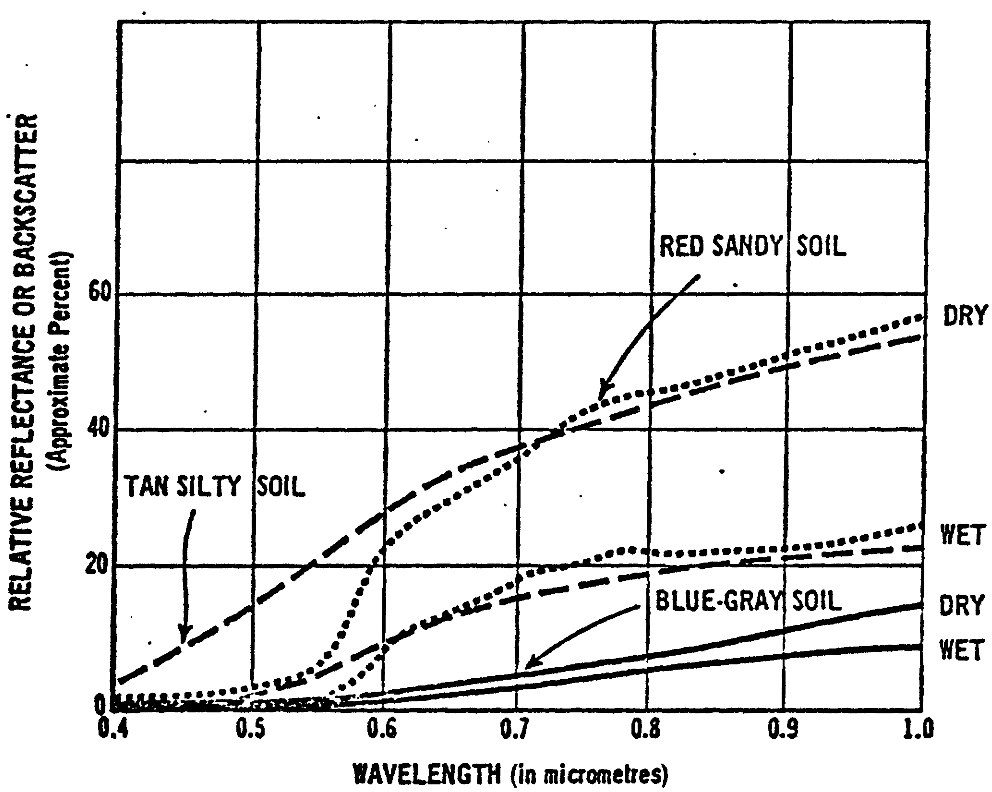


FIGURE 8: Spectral characteristics of Soils, data from H.R. Condit, 1970

IDEALIZED CURVES SHOWING RELATIVE REFLECTANCE OR BACKSCATTER FROM COVER TYPES

BACKSCATTER FROM COVER TYPES

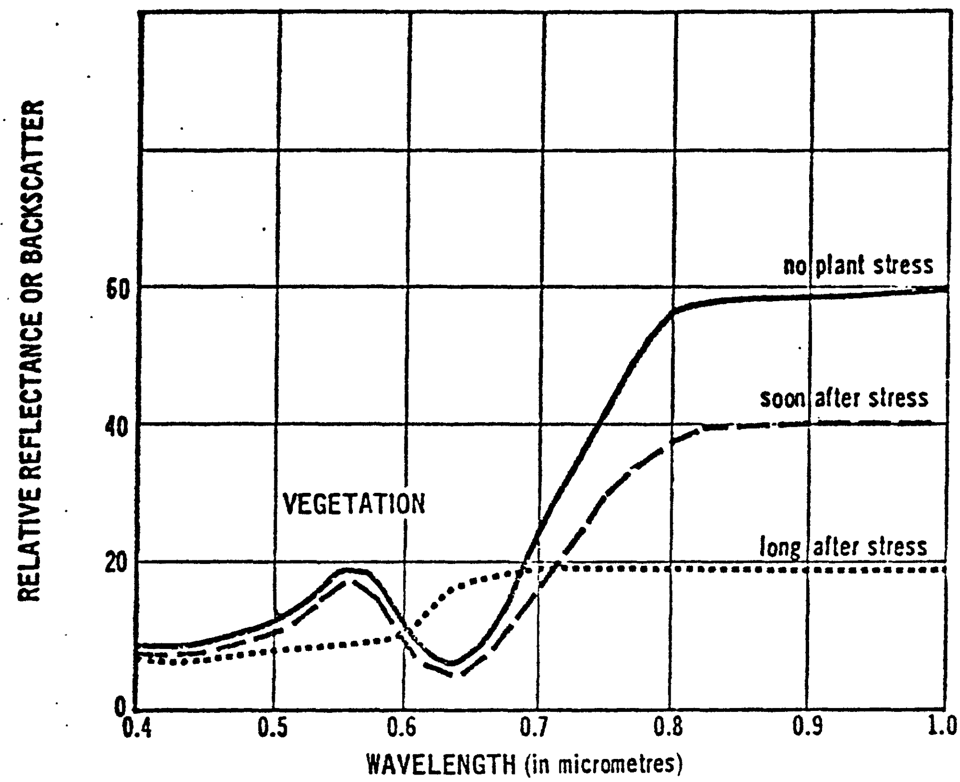


FIGURE 9: Spectral characteristics of vegetation showing decrease in infrared response because of stress. Data from Remote Sensing in Ecology, Philip L. Johnson Ed., 1969

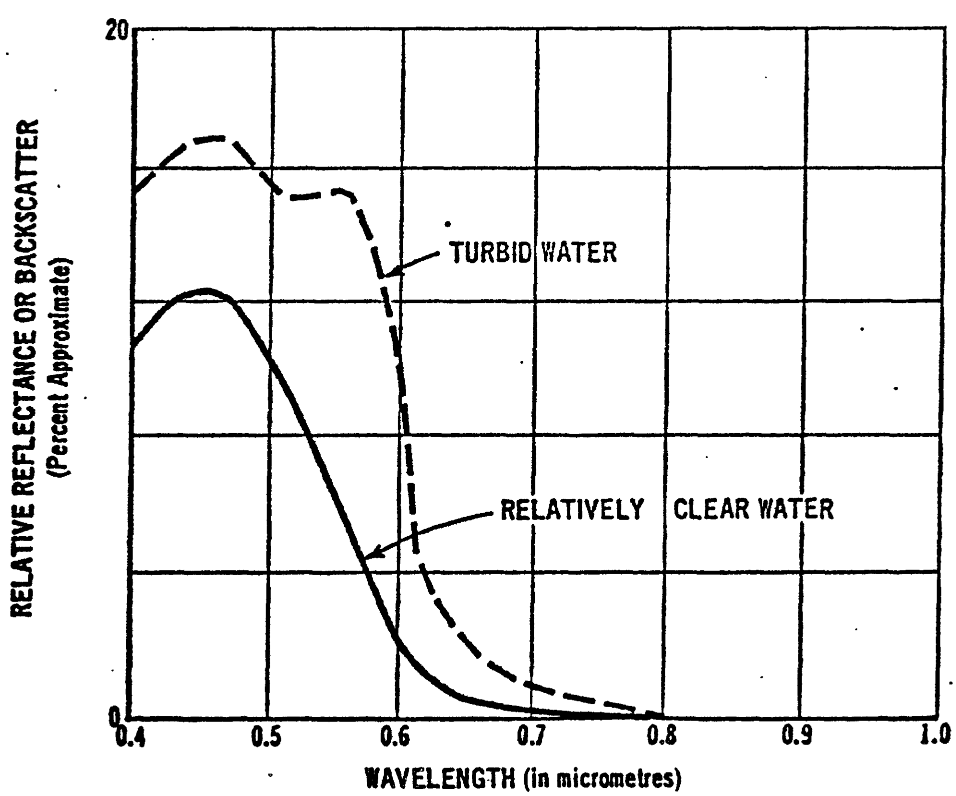


FIGURE 10: Spectral characteristics of backscattered EMR from water. Data from Polcyn and Lyzenga, 1973 and G. Moore personal communication.

illuminated throughout the day. If the ridge is oriented at right angles to the ground track of the Sun, in the morning the side facing the Sun will be brightly illuminated while the side facing away will be in the shade. These conditions will change until both sides will be equally illuminated at noon, and conditions will be reversed at sunset. In the early morning and late afternoon the Sun's rays have a small angle with the Earth's surface. Photography taken under these conditions is referred to as low Sun angle photography. Topographic trends not oriented along the Sun's ground track will be subjected to varying degrees of differential solar illumination. Areas located at latitudes progressively north or south of the location where the Sun's rays strike the Earth perpendicularly at noon are illuminated at progressively smaller (lower) Sun angles for a particular time of day. At higher latitudes, during winter months, the Sun's rays strike the Earth's surface at lower angles than in summer months. Solar-elevation angle relationships for the Landsat satellite system are shown in figures 11 and 12. Low sun-angle illumination of sloping topography is shown in figure 13. Topography in shadow is illuminated only by scattered blue skylight and by backscattered radiation from adjacent sloping topography.

ANALYSIS OF REMOTELY SENSED DATA

Imagery.--Most remotely-sensed data used in geologic analysis consist of imagery, whether it is aerial photography, a multiband color-additive display, or a digitally-enhanced cathode-ray-tube color display. Imagery displays colors or tones representing detected spectroradiometric responses of surficial materials.

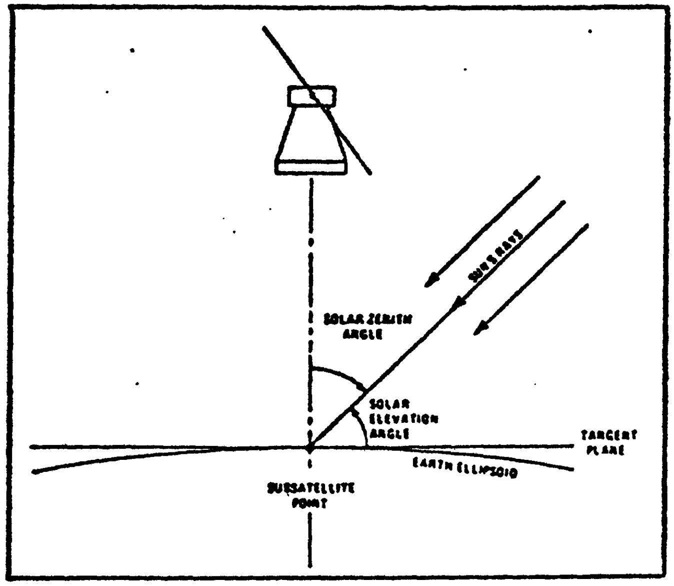


Figure 11: Solar Elevation Angle. Figure from NASA ERTS Data Users Handbook.

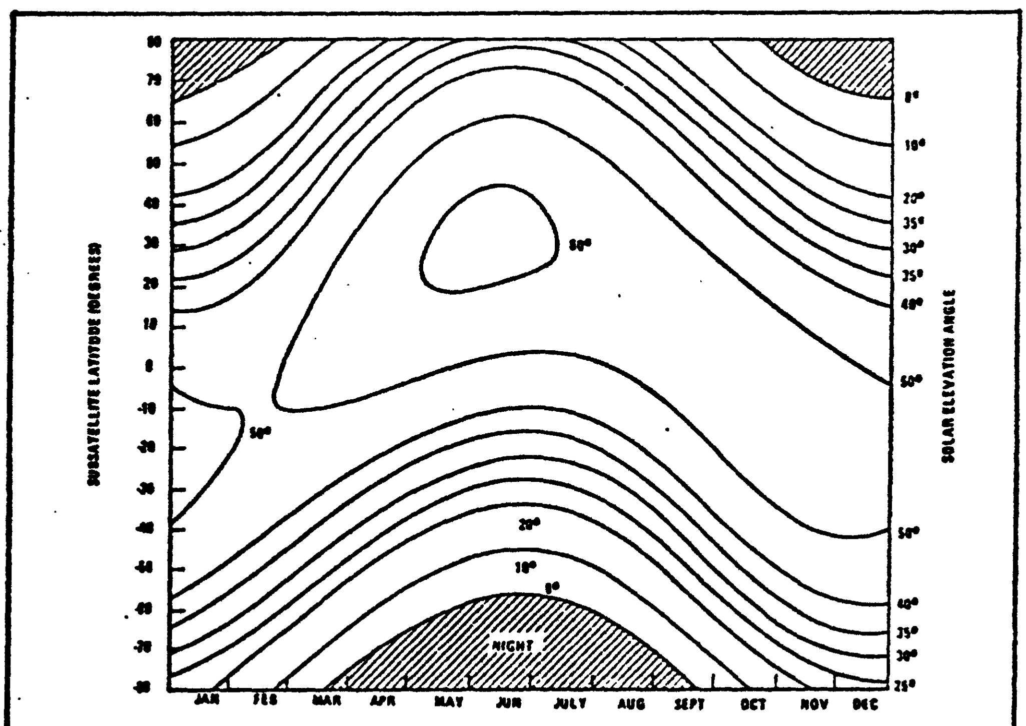


Figure 12: Solar elevation angle history for the Landsat Satellite System as a function of latitude. Satellite crosses equator at 9:42 AM (Descending Node). Figure from NASA Data Users Handbook.

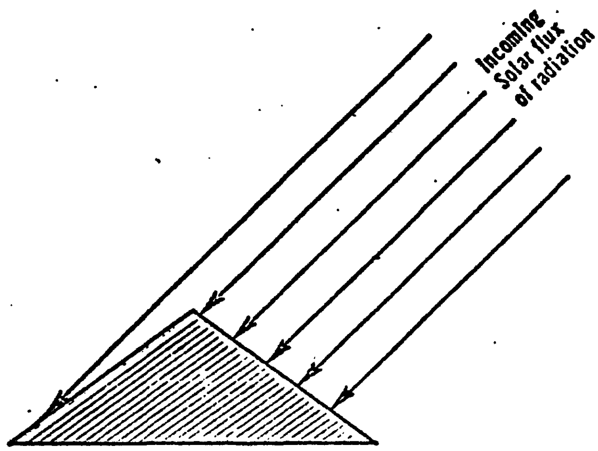


Figure 12: Incoming solar flux of radiation striking topography in slope. The slope facing the source of illumination receives four times the energy per unit area as the slope facing away.

Image formation.--The Landsat system provides an example of how radiometric responses of the Earth's surface are sampled, recorded, and displayed on imagery. The multispectral scanner (MSS) in Landsat measures portions of the flux of EMR from a 79 metre by 79 metre area at any instant in time. This measurement is made over 3,240 times along a 185 kilometer line. The resulting areas (taking overlap into account) are approximately 79 metres by 57 metres and each area is referred to as a picture element (pixel). Approximately 2,250 lines are required to produce a single frame of Landsat imagery 185 km by 178 km. Some 7.3 million pixels are present as the smallest resolution element on a single Landsat image covering 32,930 square km. In each pixel, the MSS has recorded spectral reflectance in four wavelength bands:

Band 4: 0.5 to 0.6 μm (visible green)
Band 5: 0.6 to 0.7 μm (visible red)
Band 6: 0.7 to 0.8 μm (reflected solar infrared)
Band 7: 0.8 to 1.1 μm (reflected solar infrared)

The amount of energy recorded for each pixel (pixel brightness) in any one band is a function of the percent of each surface material within the area of the pixel and the amount of EMR reflected by each surface material.

Image scale and image resolution.--Image scale is defined as the ratio of the measured distance between two points on imagery to the measured distance between the same two points on the ground. The smaller the value of the ratio, the smaller the scale of the imagery. A 1:1,000,000 scale Landsat image is referred to as small scale in contrast to large scale aerial mapping photographs at 1:20,000 scale. Areal coverage of an 18.5 by 17.8 cm Landsat image is 32,920 square kilometers, compared to over 18 square kilometers covered by a standard 9x9 inch (nominal size) aerial mapping print. The combination of aircraft and satellite imagery now available provides a variety of different scales of imagery for analysis of the Earth's surface.

Image resolution is defined as a measure of the smallest ground radiometric element that can be recorded on an image. Resolution of a radiometric element on imagery is a function of:

1. Dimensions of the ground element.
2. The difference in reflected or emitted radiometric energy between the ground element and its background.
3. The shape and orientation of the ground element with respect to illuminating radiation.

4. The resolving characteristics of the imaging system. The system's spectral, radiometric, and spatial (areal) resolving power.

5. Location of ground element with respect to nadir.

Detection of a resolved radiometric element by an analyst is dependent upon the following:

1. The contrast in reflected or emitted radiometric energy between the radiometric element and surrounding radiometric background.
2. The radiometric uniformity of surrounding background against which the radiometric element is imaged.
3. The areal extent of the radiometric background.
4. The regularity of the shape of the radiometric element.
5. The ratio of the radiometric element's length to width.
6. The regularity of groups of similar radiometric elements.

Table 3 shows the size of areas resolved on the ground increases as image scale decreases for photographic systems. Radiometric elements resolved on imagery are not necessarily detected by analysts. Even when an interpreter detects a radiometric element it does not directly follow that they are easily identified objects. Detected radiometric elements that are of a size and radiometric nature close to the limits of system resolution are usually difficult to identify.

Integration of spectral response.--The size of the minimum area resolved by an imaging system can be important in the detection of spectral characteristics of surficial materials. If brown sandstone,

Table 3.--Ground resolution on imagery available for most natural cover types

SCALE OF UNENLARGED DATA	TYPE OF IMAGERY	USUAL MINIMUM AREA DETECTED BY INTERPRETERS
1:20,000	Black and White Mapping Photography[1/]	1 square metre
1:70,000	Black and White Mapping Photography[1/]	8 square metres
1:120,000	Color Reconnaissance Photography[1/]	20 square metres
1:950,000	Color Skylab Photography (S-190B)[2/]	400 square metres
1:3,370,000	Landsat Imagery (MSS)[3/]	10,000 square metres

1/ Ground resolution is primarily limited by camera and film resolution.

2/ Skylab S-190B camera system has better resolution than most aerial mapping camera systems.

3/ Landsat system resolution is limited by the instantaneous field of view of the multispectral scanner.

tan soil, and green vegetation were present in equal amounts in an area covered by a Landsat pixel, figure 6 shows that reflectance from green vegetation would mostly account for the digital value (brightness value) of EMR recorded in MSS bands 4 and 7. However, the digital value of the pixel would be more if there were 100 percent vegetative cover. Similarly if the pixel contained equal amounts of only soil and sandstone then sandstone would mostly account for the value of EMR recorded in band 4, but soil would mostly account for the value recorded in band 7. In each case the digital value in each band would be less than if the entire pixel area consisted of the material with the highest reflectance in that band.

Consider the same two conditions as described above for bands 5 and 6. All three materials (vegetation, soil, and sandstone) have about the same average reflectance (about the same area under the curve). Thus any mixture of these materials in the pixel area would have the same digital value, in bands 5 and 6, as a pixel area covered entirely by one material.

All imagery can be expected to possess the characteristics summarized above, but larger scale, higher-resolution imagery may more accurately define the spectral characteristics of surficial materials when the same wavelength bands are used. This is because the detected EMR is reflected from fewer different surface material types as the resolved ground area decreases.

SURFICIAL GEOLOGIC ANALYSIS

Technique.--The basic techniques for landscape analysis were developed by photogeologists over 50 years ago. These techniques were developed for the stereoscopic analysis of black and white, low-altitude aerial photographs. An automatic data processing system that will successfully analyze the enormous variety of surficial features has yet to be constructed. Geologists must, therefore, rely on their experience and understanding of the fundamental principles of systematic pattern recognition to successfully evaluate the significance of the Earth's landscape.

Cover types.--It has previously been stated that geological remote-sensing tools generally detect electromagnetic radiation that emanates from the upper millimeter of the Earth's surface; interpreters of remotely-sensed data cannot "see through" soils, grass, and unconsolidated earth materials in mapping consolidated rocks with geologic remote-sensing techniques.

The natural surface of the Earth is composed of a diversified combination of cover types, and rarely are unweathered, bare rock materials exposed at the surface. More frequently, consolidated rocks at the surface are altered by chemical and biological agents, are covered by unconsolidated rock materials, contain or are covered by water, or have soils mantling them. Lichens often coat bare rocks, or grasses, shrubs, and trees obscure the soils on which they have developed. Man often obliterates natural surface cover and, in its place, erects structures or plants crops. The ground-based geologist maps geological units throughout an area of interest by (1) inter-polating between rock exposures, (2) using rock fragments exposed in soils, (3) using residual soil associations, (4) using plant associations, and (5) projecting geometric attitudes of exposed rock strata through areas dominated by other cover types. Because geological remote-sensing techniques can only measure EMR reflected or emitted from the Earth's surface, geologists should understand the following about landscape surface cover:

1. The physical and physiological characteristics of landscape cover types.
2. The effects of different climatic and physiographic environments on landscape cover types.
3. How electromagnetic radiation interacts with and emits from different landscape cover types.
4. The association of landscape cover types with geological relationships.

The major types of surface cover of geologic interest are as follows:

1. Natural surface cover
    a. Consolidated rock cover
    b. Unconsolidated rock cover (alluvium, colluvium, etc.)
    c. Soil cover
    d. Vegetation cover
    e. Water cover (including snow)
2. Cultural surface cover
    a. Man-made structures (cities, roads, houses, etc.)
    b. Agricultural surface cover (crops, pasture, etc.)
    c. Altered surface cover (logging, stream channelization)

Topography.--Differential illumination of the Earth's surface topography by EMR has several major effects which influence the interpretation of remotely-sensed data:

1. Topography facing the source of EMR will have a higher reflectance than topography facing away. This is because the amount of sunlight incident per unit area (radiance) is less on slopes facing away from the Sun, (refer to figure 13). Note that the slope facing away from the Sun will receive the same amount of skylight as the slope facing the Sun. Both slopes will also be illuminated by wavelengths of EMR scattered from adjacent sloping topography. Thus, not only is the total amount of incident EMR (flux) different on opposed slopes, but the spectral composition of EMR incident on opposed slopes is usually different as well. Topography covered by a single landscape cover type that is differentially illuminated by EMR may appear to be covered by two spectrally different cover types. The effect of differential illumination can mask real reflectance differences for materials on opposed slopes. The amount of radiation absorbed on opposed slopes will also be different under the above conditions, and thus the same relationships can exist for emitted heat radiation.
2. Differential illumination by the Sun at higher latitudes causes different ground cover types to develop on slopes facing away from the Sun, as opposed to slopes facing the Sun.

3. The shadowing effect caused by differential illumination of topography by EMR may greatly assist interpretation of remotely-sensed data, particularly if these data are not in a format that may be viewed stereoscopically. This is particularly true for topographic elements not oriented parallel to the direction of illumination. Detection and identification of landforms oriented parallel to the azimuth of incoming, illuminating EMR may be more difficult because both sides of the ridge are equally illuminated. Thus, an interpretative bias may be introduced when differentially illuminated terrain is to be evaluated.

Landscape patterns.--Landscape patterns are composed of elements that indicate physical, biological, and cultural components of the landscape. Similar conditions in similar environments produce similar landscape patterns, and unlike conditions are expressed by different patterns. Image interpretation involves a stepwise procedure that can be summarized as follows:

1. Detect, delineate, and classify radiometric data displayed on an image.
2. Recognize symmetrical distribution of radiometric elements (patterns) on imagery.
3. Identify landscape surface characteristics through systematic pattern analysis of relief, landforms, drainage, and cover types.

Some image characteristics which allow geologists to evaluate the radiometric attributes of remote-sensor data are summarized as follows:

1. Tone: The degree of brightness, ranging from dark to light. A degree of brightness is often referred to as a "gray level" and is considered to be a relative measure of the amount of EMR reflected or radiated from materials on the Earth's surface. The average interpreter can distinguish about eight "gray" levels on imagery, and up to 16 levels if the tone changes are abrupt.
2. Color: Visible color results from the interaction of specific wavelengths of visible EMR with the eye. When blue, green, and red wavelengths of visible EMR are presented to the eye in equal amounts, the result is white. Hue (magenta, purple, etc.), brightness (light blue vs dark blue, etc.) and saturation or color purity (green vs blue-green, etc.) are three variables used to describe colors. The human eye can distinguish about 8,000 hues of color.

These radiometric attributes are individually uninformative with respect to geological analysis of imagery; however, their arrangements (their patterns) on imagery allow geologists to deduce the following landscape characteristics:

1. Landforms: The size, shape, position, and association of topographic elements in the landscape.

2. <u>Drainage</u>: Drainage patterns, drainage density (drainage texture), cross-sectional geometry of valleys and width of stream channels.

3. <u>Cover types</u>: The spatial arrangement, symmetry, variability (texture), and association of landscape cover types.

To those experienced in photo analysis, these listings should not appear new. The importance of understanding the significance of landscape pattern elements cannot be over emphasized when useful geological information is to be extracted from remote-sensor data. A partial list of key references on the subject of systematic landscape pattern analysis appears as Appendix A.

BASES FOR GEOLOGIC INTERPRETATION FROM IMAGE DATA

Geologic interpretation of remotely-sensed image data is ultimately dependent upon four factors:

1. The geologist's understanding of the fundamental aspects of image formation.
2. The geologist's ability to detect, delineate, and classify radiometric image data; recognize patterns; and identify landscape surface characteristics as expressed on imagery.
3. The geologist's ability to interpret geomorphic processes from their static, surface expression as landscape characteristics on imagery.
4. The geologist's ability to conceptualize dynamic processes both above and below the surface responsible for the evolution of features expressed on imagery.

In the interpretative process, the first two factors in the foregoing list are directly related to static elements displayed on the imagery. Correct identification of landscape characteristics is dependent on an understanding of the physical principles governing the interaction of EMR with the Earth and its detection by a remote-sensor system. Interpretation of the static elements displayed on imagery, is referred to as an "image interpretation" and defines the surface characteristics ov the coverage area. In contrast to the first two factors, the last two factors are related to both static and dynamic elements that are not detected by the sensor and are not displayed on imagery. If all four factors are applied in interpreting imagery, a "geologic interpretation" is derived. A geologic interpretation integrates surface characteristics of the landscape with subsurface geologic relationships. Differences between the two types of interpretation are primarily related to the differences between identification of static surface relationships on imagery and interpretation of surface processes and subsurface relationships. The third factor in geologic interpretation from imagery relates relief, landforms, drainage, and cover types to the temporal aspects of fluvial, glacial, eolian, extrusive igneous, or surficial gravity processes. The last factor relates all of the factors previously considered in image interpretation and stratigraphic, structural, intrusive, and metamorphic attributes to the temporal aspects of tectonic, igneous, diagenetic, and metamorphic processes.

Interpretation of remotely sensed data on imagery is, in many respects, analogous to interpretation of ground-based data. Geologic interpreters detect, delineate, classify, recognize, identify, project, and conceptualize in an orderly fashion. The geologist can generally "see" no deeper into surficial cover types than a remote sensing device. The only difference is the relative scale of observation. Remote sensing imagery instantly provides data from areas many times larger than the ground-based geologist can see. Regardless of what or who has collected the data, a geologic interpretation of what cannot be seen can be derived only by an individual trained in geology.

INTEGRATION OF DIFFERENT SCALES OF ANALYSIS

Analysis of remotely sensed data is accomplished through recognition of symmetrical distributions of image elements (tone, color; that is, data) displayed on imagery. These symmetrical distributions of the elements are referred to as patterns. Patterns are differentiated on the bases of their size, shape, and internal organization or homogeneity. If "similar patterns reflect similar static conditions", then the similarity of static conditions reflected by two similar patterns must include the patterns' sizes.

During the course of analysis, it is both convenient and efficient for the analyst to proceed by first looking for the largest patterns displayed on the imagery, and then, within these patterns, attempt to recognize the next successive set of smaller patterns. Through this analytical procedure, it is possible to associate each larger pattern with the set of smaller patterns that comprise it. The association of a larger pattern with its constituent smaller patterns is important for the identification of the larger pattern. An example of this association applied to the identification and interpretation of patterns is given as follows. A flat bottomed valley, identified on the basis of a large pattern's organization, shape, and size may not be interpreted as a flood plain until the analyst identifies a river system with natural levees from smaller patterns within the valley. The necessity of identifying patterns within patterns, etc., and associating patterns, to derive a valid interpretation of the larger pattern, is evident.

The term "scale", when applied to the analysis of patterns on imagery is quite different from the scale of the imagery itself. Several "scales of analysis" are possible on imagery of a given scale. The closer an analyst gets to an image, the more detail he sees; the farther he is from the image, the less detail he sees. The amount of data on the image is constant and is limited by the resolving capabilities of the remote sensor image system. In contrast, the amount of data on the image detected by the analyst is determined by the resolving power of the analyst's eyes, his distance from the image, and by his position and angle of viewing.

It is important to note that image scale has no bearing upon the "scale of analysis"; however, the dimensions of the image and the smallest image data element impose upper and lower limits, respectively, on the "scale of analysis". If a pattern on an image cannot be identified and cannot be subdivided into smaller constituent patterns, either an enlarged image or higher-resolution larger-scale imagery may be required. Figure 14 illustrates the utility of employing several

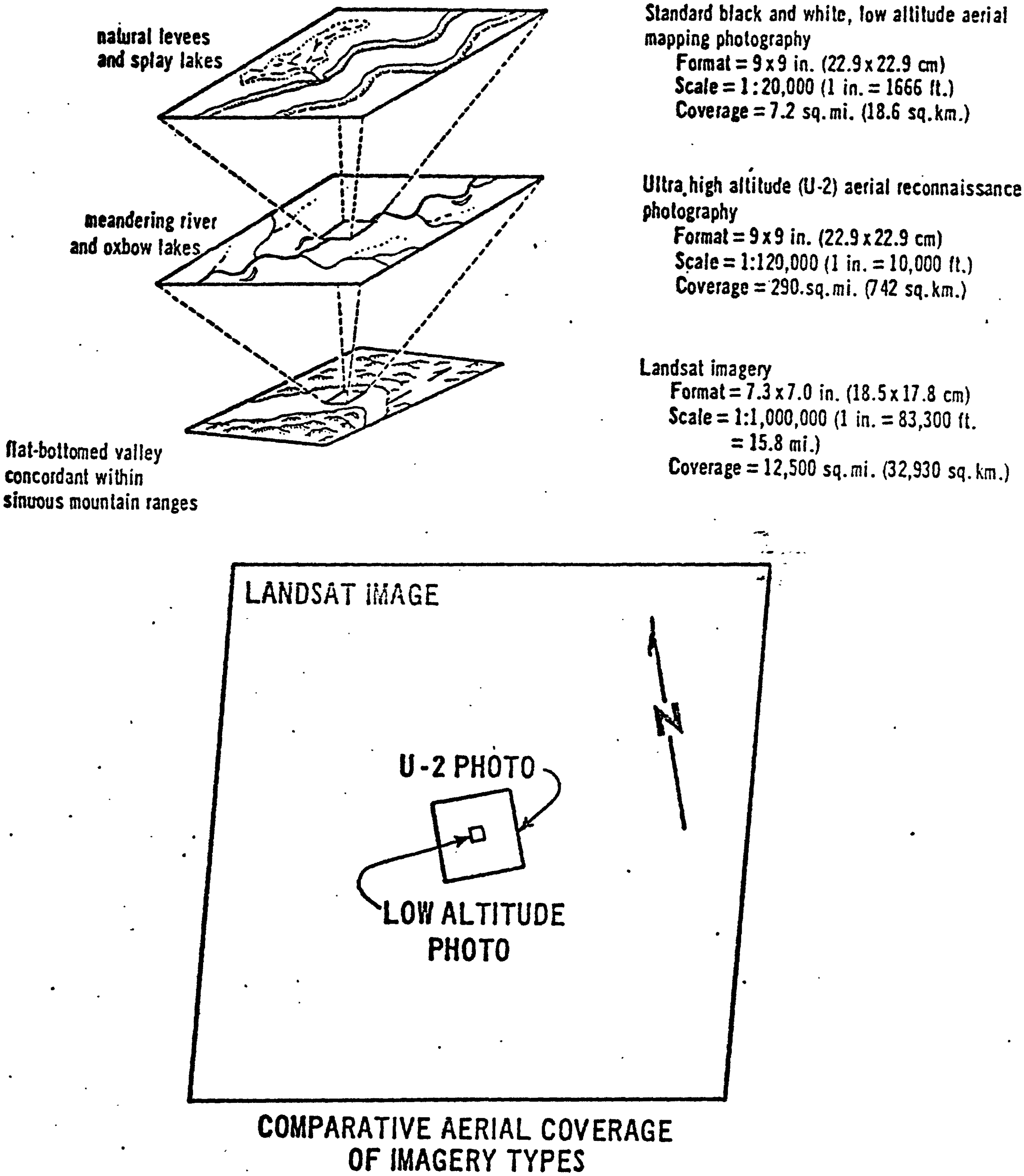


Figure 14: Illustration of different scales of imagery that may be utilized to recognize patterns on successively smaller scales of analysis.

types (and scales) of imagery in obtaining recognizable patterns that may be continuously analyzed on successively smaller scales of analysis.

GEOLOGIC IMPORTANCE OF TEMPORAL ANALYSIS

In some areas landscape characteristics change throughout the year primarily because surface conditions change with season. Prior to the launch of Landsat the importance of the time of year in data acquisition was not fully appreciated by geological analysts. The Landsat system currently consists of two data acquisition satellites that follow each other in orbit. If weather conditions permit, the two satellites may be used to collect ground data over approximately the same area every nine days. Using this type of repetitive coverage, phenological changes in vegetation; changes in the amount of moisture contained in soils, rocks, and plants; and in some areas, changes in snow cover can be observed. Identification of lineaments is greatly assisted by low-sun-angle illumination in winter months and can be aided by thin, but continuous, snow cover. In arid regions, annual vegetation often thrives in locations where ground water is near the surface. In the midwestern United States, gross Quaternary material types, formed during periods of continental glaciation, are best detected on imagery acquired in May, while landforms are best detected in early January. This is because soil moisture variations are greatest in May and soil is tilled and bare at that time of year. In some areas, plant species closely associated with certain rock types and plant reflectance differences may be greatest in spring or fall. Remote-sensor data acquired at one particular time of year may best define certain surface characteristics while data acquired at another time best define others. Both types of data may be required for a correct geologic interpretation.

DEVELOPMENT OF GEOLOGIC MODELS

In interpretation of geologic relationships developed from a particular scale of analysis, geologists are confronted with the problem of inferring relationships they cannot directly observe from any one point in the field. This problem is usually approached by constructing a three-dimensional, conceptual geologic model. The field geologist plots strikes and dips of rock strata on a map, and usually constructs structural cross-sections in the field so he can predict where to look for important relationships. The development of a geologic model in the field usually requires a number of time-consuming, widely-spaced observations. The model is developed from observations of outcrops and consists of a geologic map which displays an interpretation of geologic data in plan view, and structural cross-sections which display interpretations of surface geologic data in cross-sectional view (below the surface). Remote-sensing imagery allows the geologist to view the landscape in a synoptic format and if surface characteristics of the landscape are well defined on imagery and patterns of geologic significance can be identified, geologic models can often be rapidly developed.

The development of geological models enables analysis of field data (and imagery) to identify key areas that require analysis in greater detail (at higher resolution and larger scale). An efficient approach to the analysis of an area that is ultimately to be evaluated by ground-based methods is to employ several scales of image analysis, and eventually to integrate information derived from these analyses with data derived from field investigations. Usually geological models are developed and employed in a variety of different ways in geological analysis. Often the analyst has a preconceived geological model in mind prior to analyzing the imagery. If the preconceived geological model was developed from suitable ground data and/or from experience in similar geologic settings, landscape patterns identified on imagery can be interpreted in terms of their correlation with the model. The analysis of small-scale imagery, that covers large areas, sometimes presents problems to analysts with preconveived geological models in mind; this is because their geological experience and available ground data is often limited to small areas. An interpreter with a preconceived model in mind, may introduce bias in his interpretation and incorrectly determine geological relationships, unless care is taken to carefully consider all factors of the interpretation process. Most geologists recall the statement "you can usually go out into the field and find data to substantiate your preconceived point of view", and this statement applies to the interpretation of imagery. A good way of eliminating an interpretative bias from an analysis of imagery is to start with the smallest scale imagery available for the area to be analyzed. This imagery should be analyzed objectively using a systematic pattern recognition procedure, and without the influence of ancillary geologic information (published maps, etc.). This analysis should define regional trends and relationships (a model). The analysis should proceed to larger scales, using larger-scale imagery in key areas identified in the previous analysis, if the imagery is available. Sometimes the interpretation of small-scale imagery can be revised (the model can be refined) through analysis of larger scale imagery. Eventually a point is reached where ground data or additional remote-sensing data are required in key areas to resolve conflicts in, or confirm the validity of, the interpretation. At this point the analyst should bring as much ancillary geologic information as possible (maps, etc.) to bear on the analysis and should determine if additional information can be extracted from the imagery. The careful image analyst will plot this additional information on a separate overlay because it is easy to interject information from an existing, and not necessarily accurate, map into that derived from interpretation of imagery. This separation also allows information not appearing on the maps, etc. (new information) to be evaluated. At this point in the analysis, a conceptual geologic model should be defined, and key ground analysis areas should be identified. Remote-sensor data should be acquired over these key areas if such data will support field work and will provide additional information. Field visits to key areas may require that imagery interpretation and, consequently, the geological interpretation (the model) be revised. Often the entire analysis proceeds in an iterative fashion and culminates in large-scale, ground-based geologic mapping of site-specific target areas. The technique economically conserves resources because the entire area under analysis does not have to be completely "walked out" on the ground.

GROUND WATER EXPLORATION IN ARID ENVIRONMENTS

This section is included to illustrate how remote sensing data might be utilized to develop a geohydrologic model for ground water exploration in arid environments. Tucson, Arizona, was selected because ancillary data on ground water occurrence is well documented there. Landscape characteristics of the area that are identifiable on imagery and have geohydrologic significance are the following:

1. Landforms: The area is characterized by mountainous bedrock areas and intermontane alluvial valley areas. Linear and curvilinear valleys with steep gradients occur in bedrock areas. Alluvial fans are present at the bases of mountains. A few playa lakes occur in the valleys.
2. Drainage: Bedrock areas have coarse, rectangular-dendritic drainage patterns. In some areas, adjacent to well developed bedrock valleys, alluvial fans show medium- to coarse-textured, colinear and parallel drainage patterns. The central portions of basins have very coarse, dendritic drainage patterns and floodplains are well developed.
3. Surface cover: Riparian vegetation is localized in some basinal areas, but patterns of relatively homogeneous vegetation occur on alluvial fans.

Figure 15 is a Landsat scene covering the Tucson area. The imagery was acquired under conditions of low-sun-angle illumination that occur during winter months. Note that landforms and drainage are well displayed on this imagery. Image interpretation of

Figure 15: Landsat 1, band 7 (reflected solar infrared). Tucson, Arizona appears near the upper left corner and Wilcox Playa in the upper right. The image was acquired on December 21, 1973, under conditions of low sun angle illumination (28°). Note particularly lineaments, drainage patterns, and drainage texture.

these landscape characteristics appear on figures 16, 17, and 18. Figure 19 is a geological interpretation of the probable extension of lineaments into basin areas.

Figure 20 is a Landsat band 5 image which displays riparian vegetation, and anomalous vegetation patterns on alluvial fans. Figure 21 is an image interpretation of these vegetative surface cover types.

At this point in the analysis we go no further without bringing in ancillary information, if only Landsat imagery is employed. This information can be summarized as follows:

A. Ancillary information ("facts"):

1. Bedrock areas were uplifted and basins were downdropped by normal faulting in Cenozoic time.
2. The valleys have been partially filled with alluvial gravel, sand, silt, and clay, mostly in Pleistocene time.
3. The climate of the area was more humid in Pleistocene time than it is today.
4. Both stream flow and ground-water recharge come almost entirely from the melting of snowpack on the upper slopes of mountain areas.
5. The largest amounts of ground water occur in coarse-grained valley fill alluvium.
6. Areas having abundant soil moisture are covered by dense healthy vegetation.

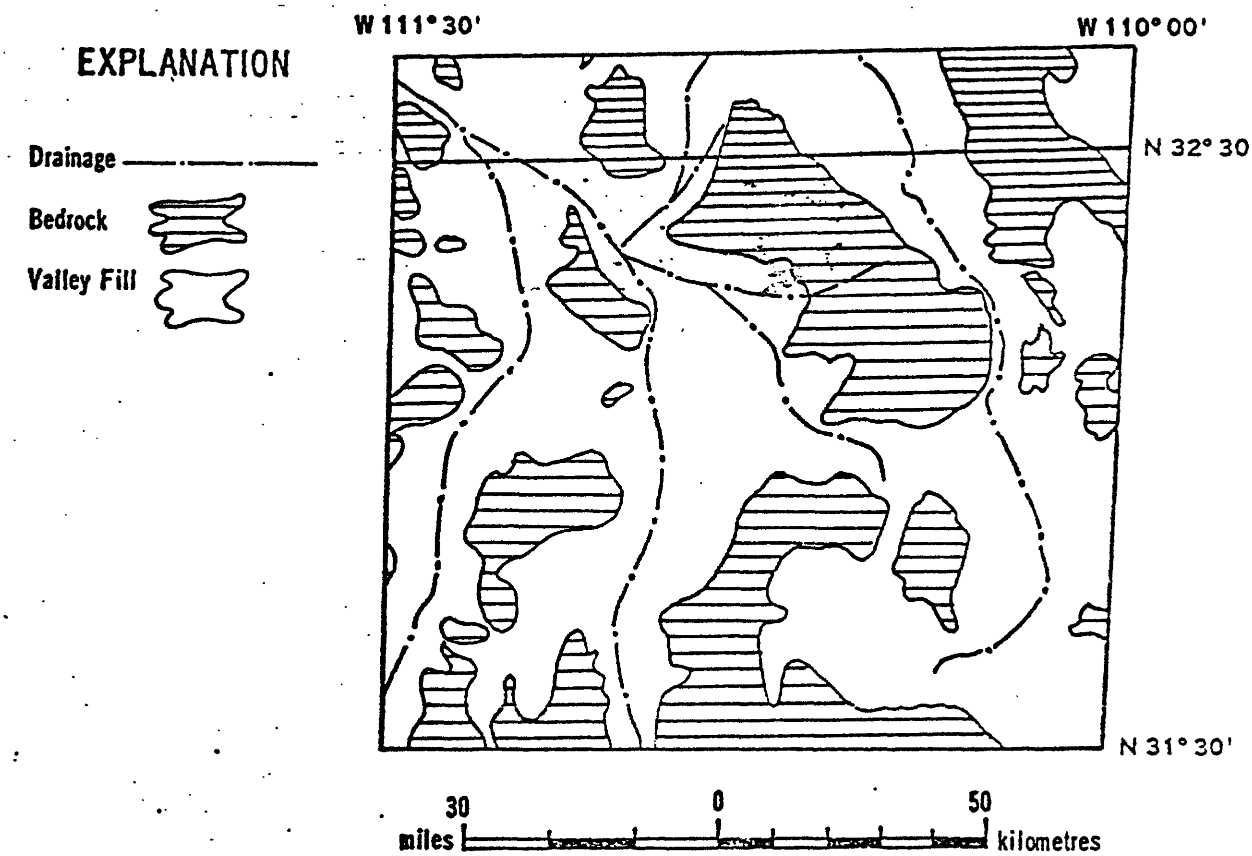


Figure 16: Image interpretation of bedrock areas, valley fill, and major stream drainage. From Landsat band 7 image, 1:1,000,000 scale. Date of image acquisition: December 21, 1973. Landsat image identification: E-1516-17250.

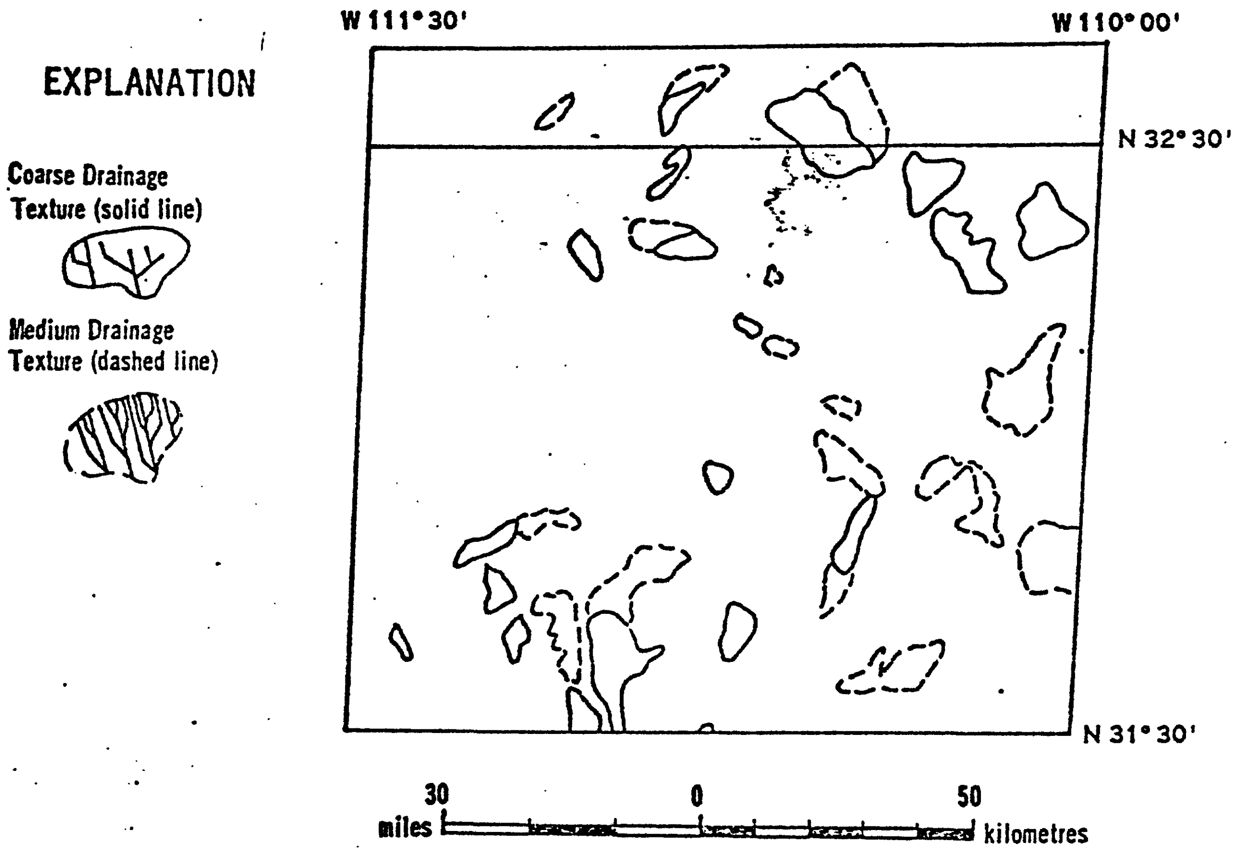


Figure 17: Image interpretation of drainage density (texture). From Landsat band 7, 1:1,000,000 scale. Date of image acquisition: December 21, 1973. Landsat image identification: E-1516-17250.

EXPLANATION

Lineaments

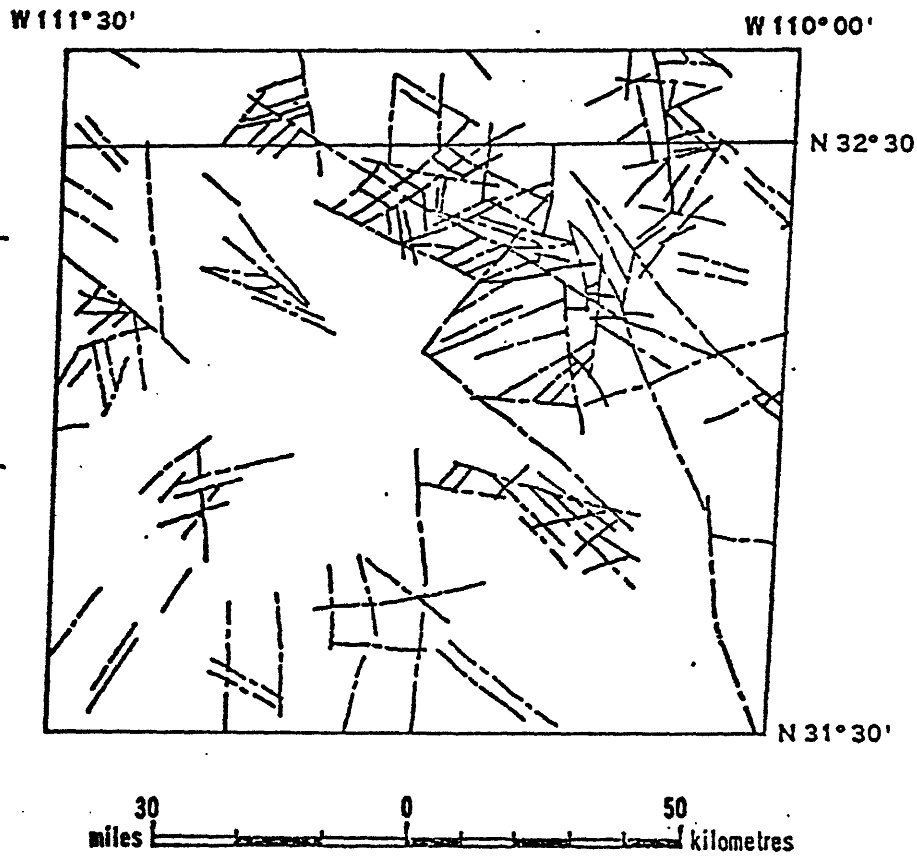


Figure 18: Image interpretation of lineaments in bedrock and adjacent valley fill. From Landsat band 7, 1:1,000,000 scale. Date of image acquisition: December 21, 1973. Landsat image identification: E-1516-17250.

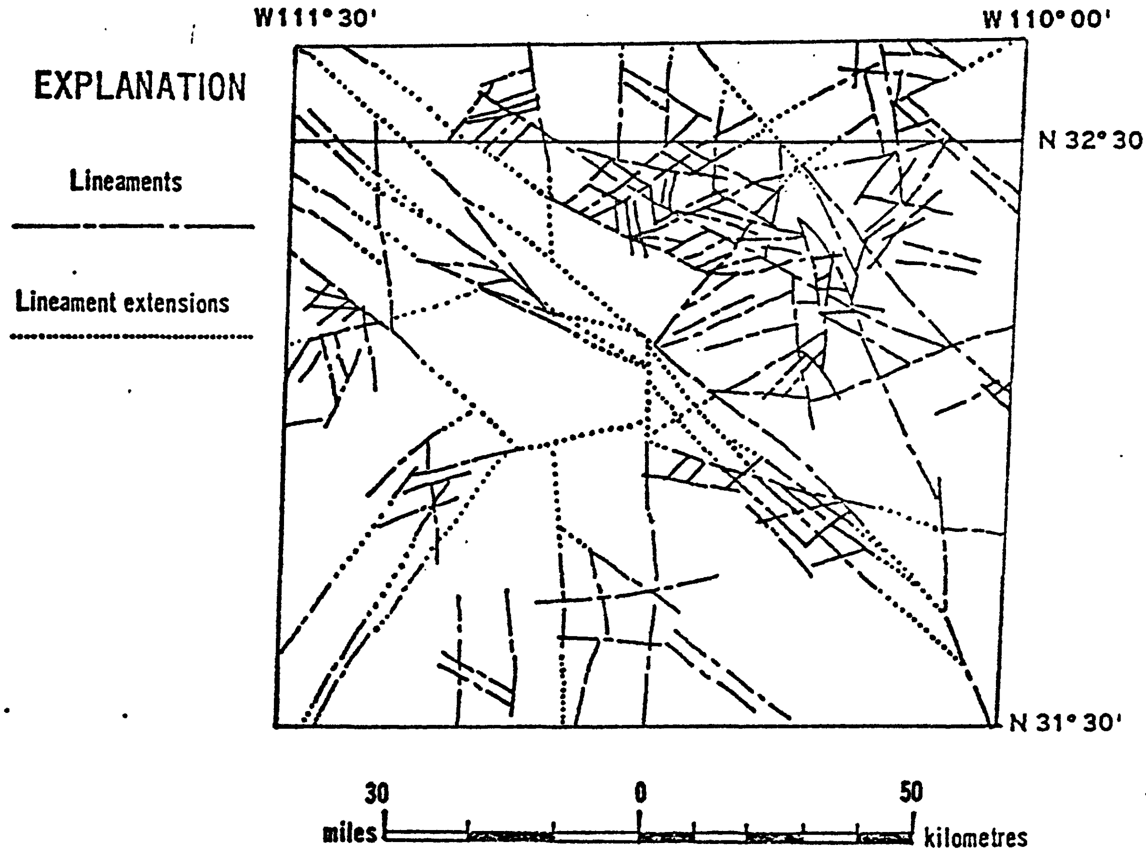


Figure 19: Interpretation of lineaments by extending lineaments into valley fill along trends. This is a geological interpretation of image information. From figure 18.

Figure 20: Landsat band 5 image of Tucson, Arizona. Date of acquisition: April 13, 1973. Image identification: E-1264-17283. Riparian vegetation shows as dark, sinuous lines in basin areas. Vegetation anomalies on alluvial fans show as darker toned patterns. Actual photo interpretation of vegetation (figure 21) was done utilizing a Landsat color composite from the same date.

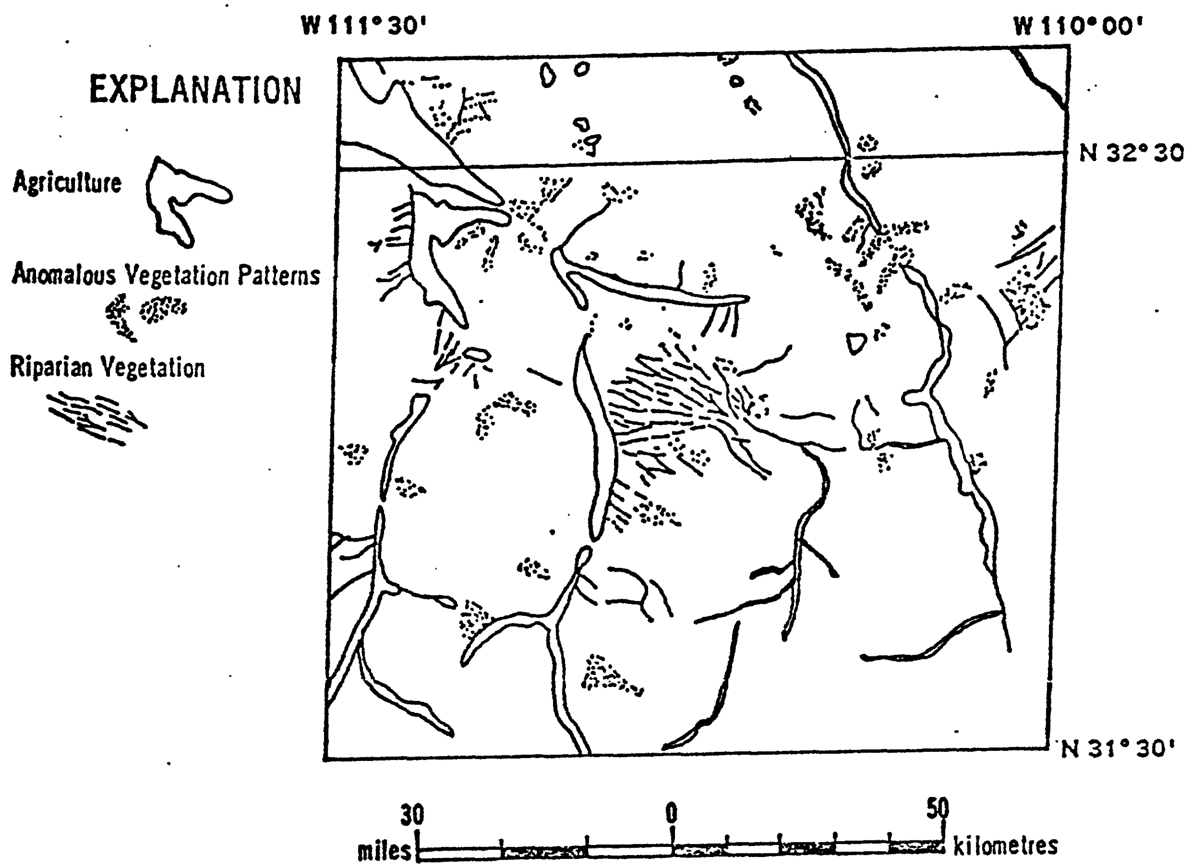


Figure 21: Image interpretation of vegetation patterns. From Landsat color composite, 1:1,000,000 scale. Date of image acquisition: April 13, 1973. Landsat Image identification: E-1264-17283. Note: Figure 20, Landsat band 5 substituted for this image in this paper.

B. Assumptions:

1. Coarse-grained aquifers are now mostly covered by finer-grained materials which were deposited in the present day arid environment.
2. Joints and faults influenced the distribution of coarse-grained materials in basin areas.
3. Lineaments mark the locations of joints and faults.
4. Coarser-grained sediments occur on the land surface in areas where drainage has a coarse- or medium-texture on Landsat imagery.
5. Most recharge to alluvial aquifers occurs where relatively coarse-grained, porous alluvium abuts bedrock.
6. Groundwater moves down gradient in the same general directions as surface streams flow.
7. Dense vegetation indicates areas where the water table may be close to the surface.

In development of a model for ground water occurence and movement in arid environments, it is important to separate facts from assumptions. By making this separation it is relatively easy to revise assumptions, as additional data becomes available.

Figure 22 is a geohydrologic interpretation of landscape patterns recognized on Landsat imagery. Figure 22 is a two-dimensional graphical display, based on a three-dimensional, conceptual geologic model, that can be used to predict ground water recharge, movement, and discharge in the Tucson area of Arizona. Based on the model, two areas have been identified for exploration The orientation of

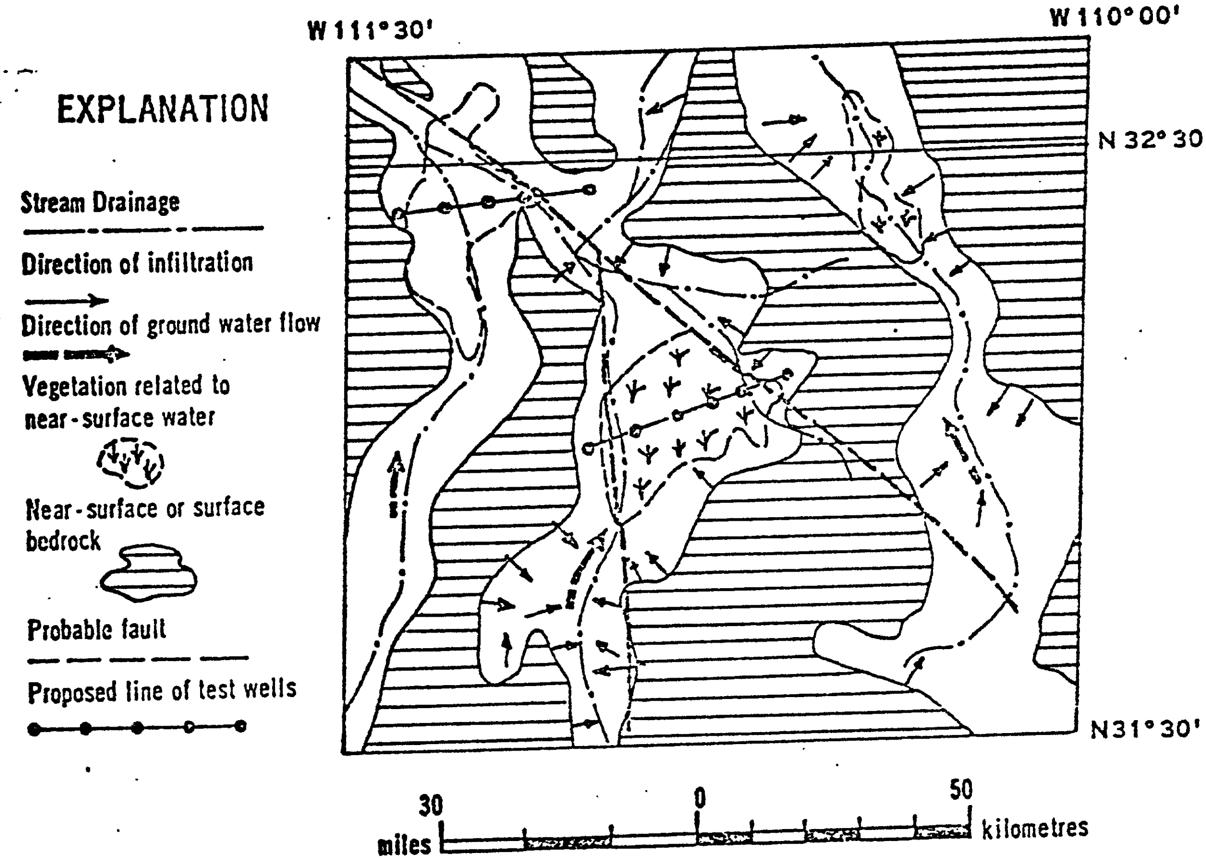


Figure 22: Geohydrologic interpretation of landscape patterns recognized on Landsat imagery. Interpreted from figures 16, 17, 19, and 21.

the proposed lines of exploration wells should define important relationships for further analysis. It should be noted that this model probably only approximates very gross ground water relationships, and that it was developed primarily for puroses of illustration. The actual ground water conditions in the Tucson area are much more complex. The proposed exploration plan, however, would have found major supplies of ground water. (See Davidson, E. S., 1973.)

TARGETING MINERAL EXPLORATION EFFORTS IN SOUTHWESTERN IDAHO

The utility of remotely-sensed imagery in providing data covering a broad area is demonstrated by this example of its application to base- and precious-metal exploration in the Pacific Northwest. A specific problem was defined in which a 36,974 square kilometre (approximately 14,443 square mile) area was to be evaluated with respect to volcano-tectonic environments potentially favorable for the localization of mineralization.

In order to determine the scale, or scales, of analysis to be undertaken in evaluating the area of interest, the specific types of information required for an interpretation were considered. The most evident required information was:

1. The location of volcanic centers within the area.
2. The location of the major structural elements within the area.

With respect to the discrimination of environments potentially favorable for base- and precious-metal mineralization, the required information was further refined to include:

1. The location of <u>felsic</u> volcanic centers that indicate some degree of magmatic differentiation (the location of mafic and felsic centers that are either superposed or in close proximity).
2. The location and orientation of <u>ruptural</u> structures (faults, fractures, joint, etc.) associated with, or in close proximity to felsic volcanic centers.

The effectiveness of methods employed in data acquisition, analysis, and interpretation is dependent upon four parameters:

1. The type of data required.
2. The amount of data and/or areal extent over which data was to be acquired.
3. The time required to collect, analyze, and interpret the data.
4. The cost of manpower and materials required for the collection, analysis, and interpretation of the data.

The type of data and area over which data was to be acquired was specified by the problem. The amount of data that could be directly acquired from surficial exposures was fixed in the area being evaluated. Regardless of the method by which the data was collected, the data had to be relevant to the specific problem and had to be displayed in formats (map and image, respectively) that could be analyzed and interpreted. The time required to collect, analyze, and interpret data varies considerably between ground-based techniques and remote-sensing methods. The difference is almost entirely a function of the time it takes to acquire the data in a format that may be analyzed. Remotely-sensed imagery is currently available at several scales, in several formats, for any season of the year and may be acquired usually within a month (dependent on order processing and shipping times). Field acquisition of data and compilation of previously published data are considerably more involved methods of collection and usually do not result in an unbiased synoptic presentation of the data. In this respect, remotely-sensed imagery was considered to be a time-saving method of acquiring relevant data in a format which could be efficiently analyzed for the defined problem. The cost of two, black and white, 1:1,000,000 scale prints of Skylab photography covering the area of interest is $6.00. The cost of transparent overlay materials, pens, stereoscope, etc., for analyzing the data should not exceed $20.00. Seven man-days expended on analysis and interpretation of the data plus seven, subsequent, man-days spent in field checking critical analytical assumptions should not exceed $1,000 plus transportation costs. It was considered doubtful that the ground-based acquisition and formating of data alone (not including analysis, interpretation, and field checking) would cost less than the entire acquisition and evaluation expense of remotely-sensed imagery for the specified problem.

The area under investigation in southwestern Idaho and southeastern Oregon is displayed on Landsat imagery, Skylab photography, NASA (U-2) reconnaissance photography, and U.S. Geological Survey standard aerial mapping photography. Both Landsat imagery and Skylab photography display the entire area or two adjoining prints, thereby affording the most synoptic (or condensed) coverage of the area. Regional structural trends and associated volcanic centers are resolved by both systems and may be recognized and identified on 1:1,000,000 scale prints. Skylab photography is more advantageous in structural analysis than Landsat imagery because it can be stereoscopically analyzed in its entirety due to the 50-percent overlap of adjacent frames. Skylab photography from August, 1973 also provides greater contrast (because of low-sun-angle shadowing) of structural features. In southwestern Idaho, late summer and autumn photography is optimal for detection and consideration of structurally-related vegetation and soil moisture patterns.

With regard to the foregoing considerations, two overlapping frames of Skylab photography were chosen for analysis. Black and white, 1:1,000,000 scale prints of adjoining August 8, 1973 scenes emphasized the surficial structural features required in the evaluation.

The analysis of the Skylab photographs required two man-days and involved the recognition and identification of patterns which were indicative of surficial volcanic materials and associated structural features. Figure 23 is the mosaic of Skylab photos (identification numbers G30A020315, G30A020316) of the study area in southwestern Idaho and adjacent southeastern Oregon.

Volcanic features identified from the association of recognized relief, landform, drainage, and cover-type patterns included calderas, cones, shields, and both fissure- and vent-type flows. Only one caldera area was characterized by light tonal elements that may be indicative of felsic volcanic materials. This area is shown on figure 24 as a cluster of circular anomalies above the center of the illustration.

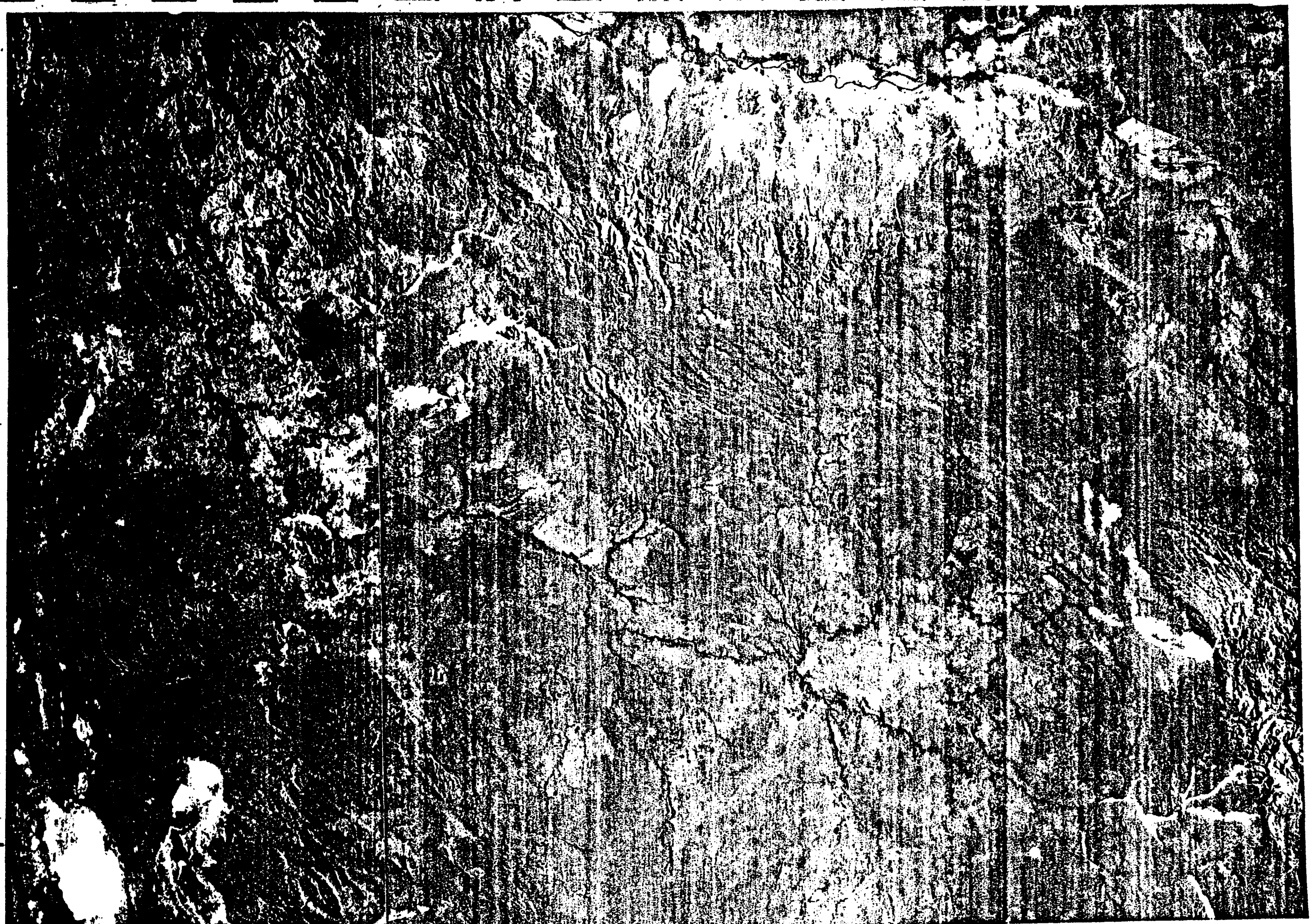


Figure 23: Overlapped Skylab photos, identification numbers G30A020315 and G30A020316. Major rivers displayed on the photos are the Snake (top center) and Owyhee (top left to lower right). The photos were taken in September, 1973 by Skylab astronauts.

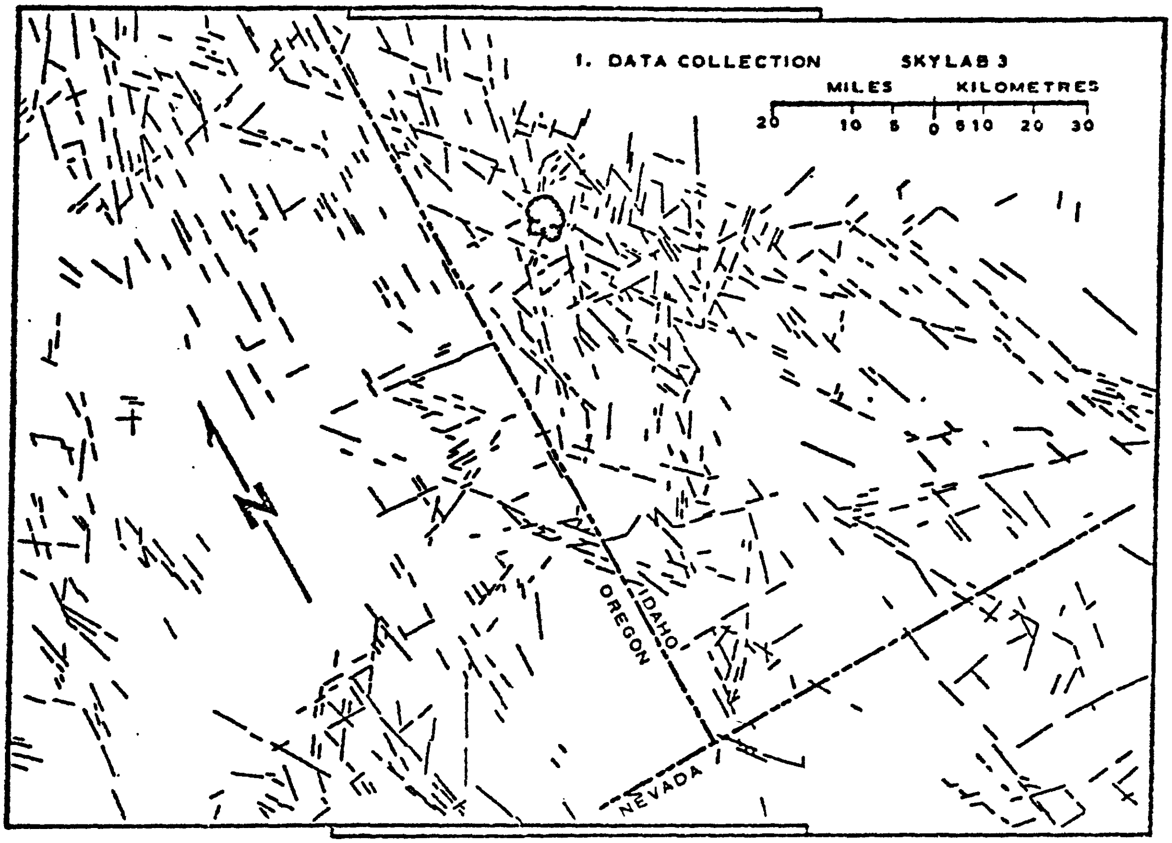


Figure 24: Caldera complex and associated linear structural elements.

Structural elements, collectively termed "lineaments", are also illustrated on figure 24. The sequence of ruptural discontinuities expressed by these "lineaments" is determined by their cross-cutting and offsetting relationships with identified landscape features. Only apparent strike-slip and approximated, apparent dip-slip displacements could be determined from the photography. An analysis of structural trends within the area is shown on figure 25. Three major alignments were noted; N40W, N5W, and N85W. A weakly developed N40E trend was also observed.

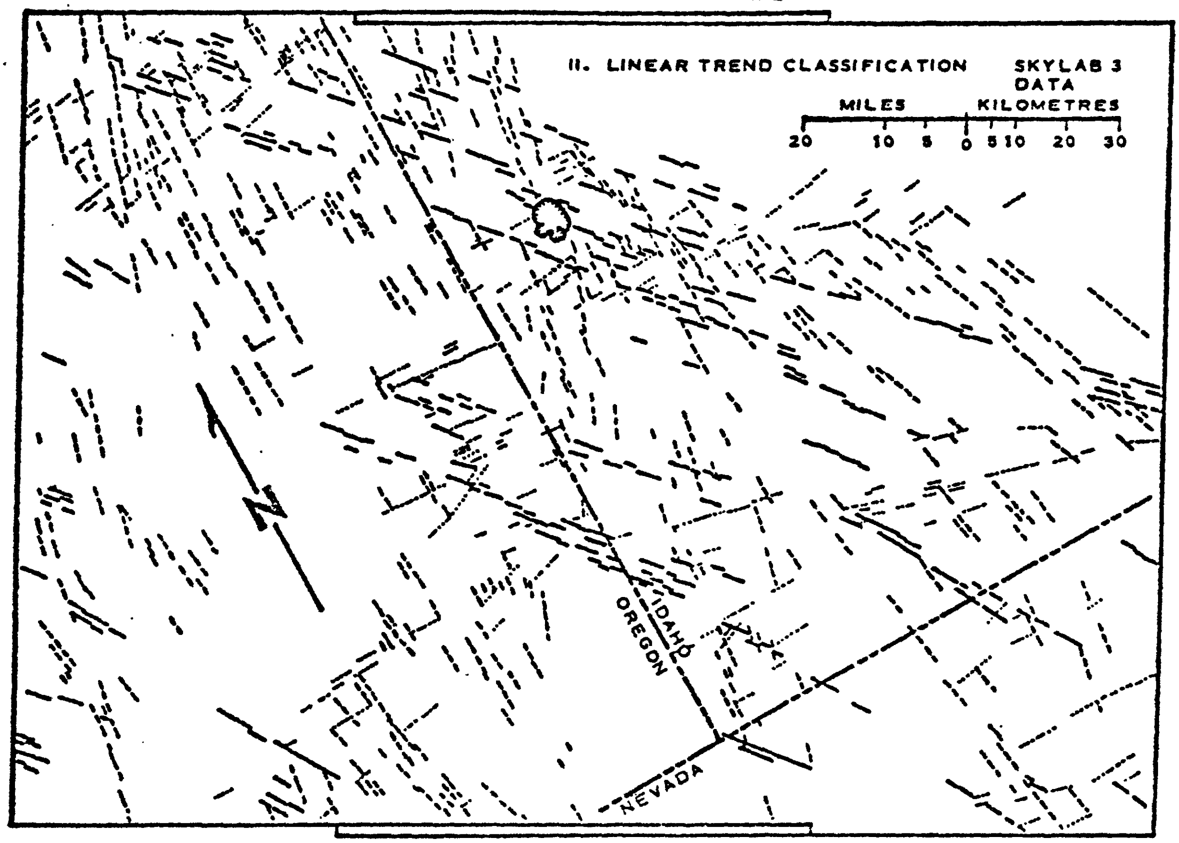


Figure 25: Accentuated major structural trends; N40W = heavy, N5W = medium, N85W = light.

Interpretation of volcanic and associated structural features within the area involved the correlation of the caldera with the structural symmetry, sequence, and apparent displacements. The resultant interpretation is illustrated in synoptic form on figure 26. Symbols in the figure represent the probable major directions of movement. The symbolized thrust elements include high-angle reverse faulting.

Ground confirmation of the interpretation derived from the analysis of Skylab photography is given in figure 27. Previous workers in the field have identified the major fault trends, but displacements are not well defined.

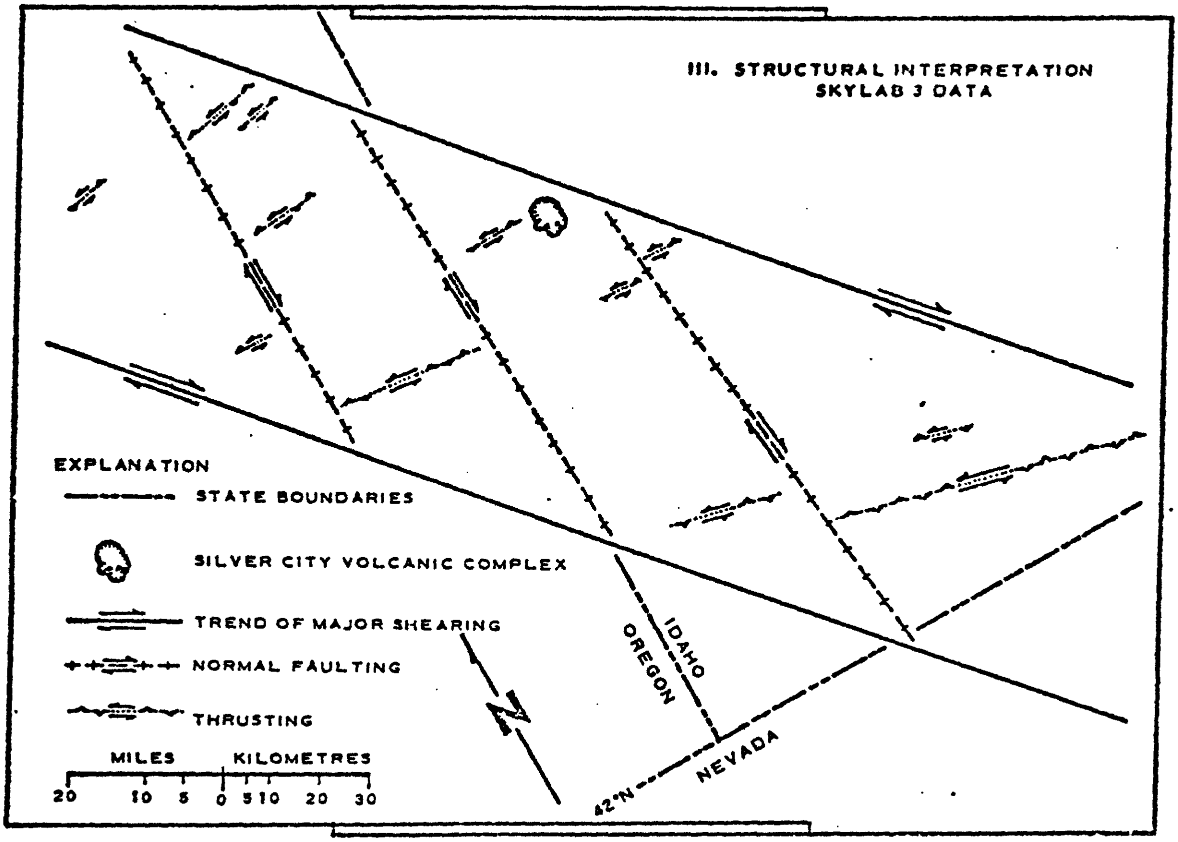


Figure 26: Simplified volcano-tectonic interpretation showing dominant movement directions along major zones of weakness.

IV. GROUND CONFIRMATION

SKYLAB ANALYSIS	MCINTYRE, 1972 REYNOLDS AREA	ASHER, 1968 SILVER CITY AREA	PANSZE, 1971	SORENSON, 1927 HALL & WALSH, 1974 SOUTH MTN. AREA
~N 40° W RIGHT-LATERAL SHEARING	N 30-50° W			N 40-50° W HI∠
		N 0-43° W 90-60° SW		
~N 5° W RIGHT-LATERAL NORMAL FAULTING	N 0-10° W N-S FOLDING	N-S FOLDING	N 10-20° W	N 0-10° W 50-70° SW FOLDS, THRUST N 10° W GRABENS
~N 85° W LEFT-LATERAL THRUSTING		N 75° W 70-75° SW 26-30° SW	N 75-85° W HI∠ S LO∠ S	N 70-90° W HI∠
~N 40° E UNIDENTIFIED MINOR TREND	N 30-40° E	N 24-50° E 50-75° E	N 66° E	N 35-55° E HI∠ N 67-75° E HI∠

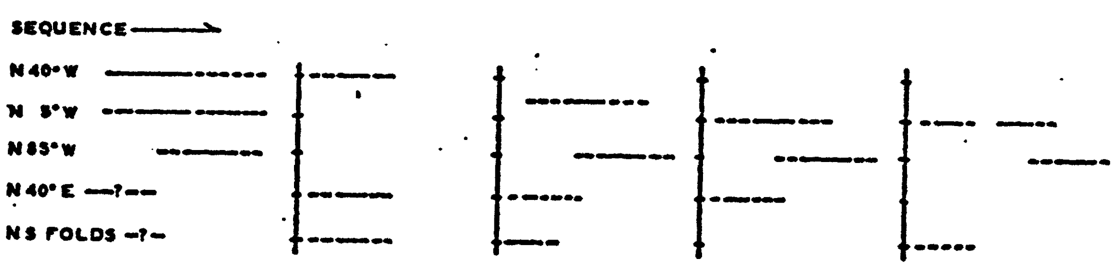


Figure 27: Correlation of interpreted fault geometries and documented field evidence.

The integration of several additional scales of analysis using remotely-sensed imagery resulted in the association of regional and local volcano-tectonic features as illustrated in figure 28. Diagram 3, within figure 28, represents the conceptualized, geologic model of features determined from Skylab analysis.

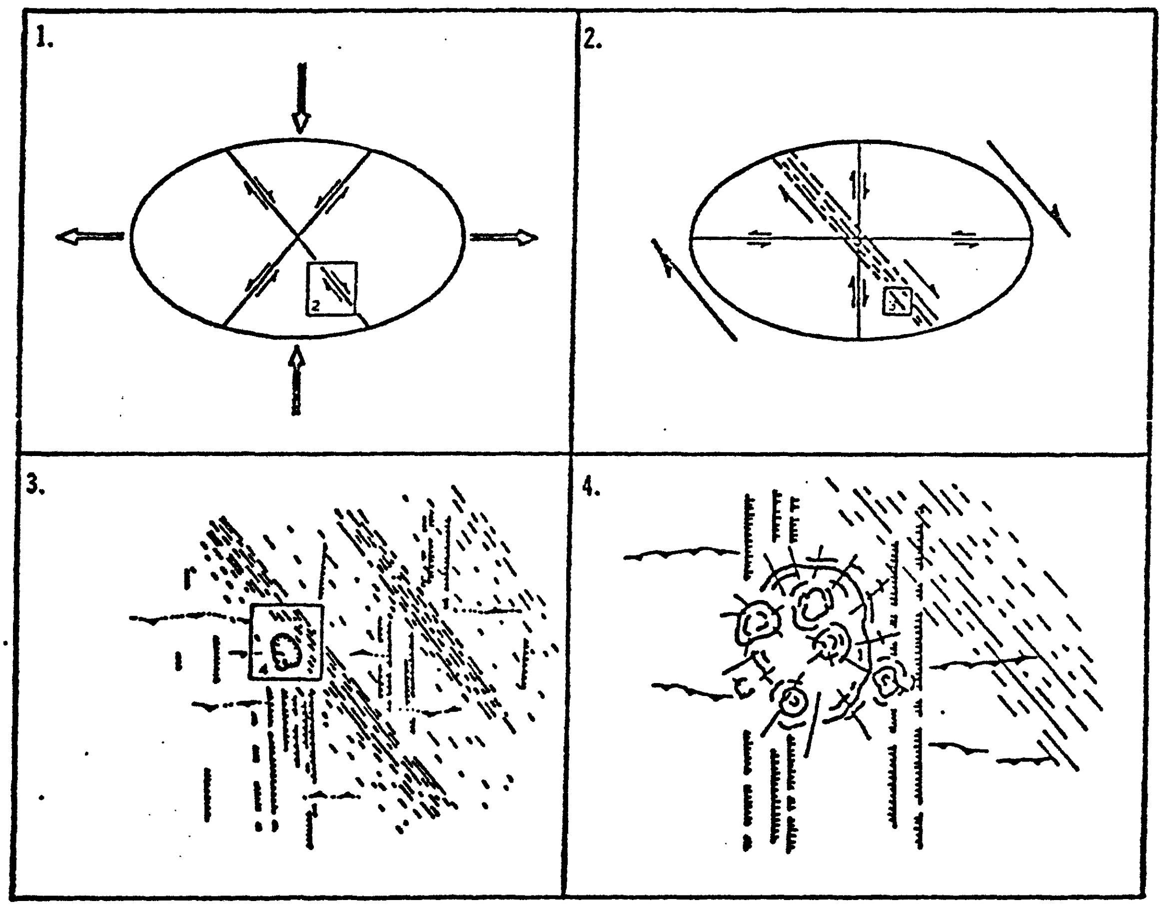


Figure 28: Synoptic geologic model of interpretations based on several scales of remotely-sensed data analysis. (1) Small-scale regional pure shear system based on analysis of 1:5,000,000 scale Landsat band 7 mosaic of conterminous U.S.; (2) Large-scale regional simple shear system based on analysis of four adjacent 1:1,000,000 scale Landsat band 7 images; (3) Skylab analysis of this example; (4) Local analysis based on NASA reconnaissance color-infrared photography (four 1:120,000 scale prints).

In this example of the utility of remotely-sensed imagery a specific problem was defined; the types of information required for the solution of the problem were deduced; the most efficient means of obtaining relevant data was decided upon; special conditions imposed by the data source, the area of interest, and types of information required of the data were considered; specific data was acquired; the data was analyzed in a systematic manner with special reference to the types of information and consequent scales of analysis required; and the resultant information was interpreted in terms of the static subsurface relationships and dynamic processes.

Other types of data and/or scales of analysis could have been acquired, evaluated, interpreted, and, subsequently, correlated with or contrasted against this initial interpretation. Additional confirmation of the geologic model could have been obtained if need, time, and money permitted. It should be realized, however, that any dynamic interpretation of static data must be substantiated by "ground truth" or field checking of critical surficial and subsurface relationships that have not been anticipated or detected prior to interpretation. This field checking is required by both ground-based and remotely-sensed data interpretation. The final test of any interpretation or geologic model is not defined in terms of its simplicity, amount of data collected and evaluated, logical argument, or scientific principle, but rather by how accurately it describes the present three-dimensional geologic environment in its application.

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APPENDIX A

This appendix lists key reference works that contain articles on image formation, image interpretation, pattern recognition, and the use of remote sensing techniques in geologic investigations. These references contain extensive bibliographies which can be effectively used to identify additional background materials.

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