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G. Bryan Bailey

REFERENCE MATERIALS ON THE CHARACTERISTICS OF THE LANDSAT SYSTEM FOR MINERAL AND PETROLEUM EXPLORATION

EROS DATA CENTER

U. S. Geological Survey

Sioux Falls, South Dakota

These reference materials were prepared for training courses in geological remote sensing at the EROS Data Center. The materials are a supplement to lectures illustrated with 35mm slides. Slides are available from the EROS Data Center Public Affairs Office if the illustration has a PAO number (E-00000-35) located on it. This PAO number should be referenced when slides are ordered.

James V. Taranik
U. S. Geological Survey

October 1977

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INTRODUCTION

These materials were largely developed from two references; the NASA Landsat Data Users Handbook and Thomas, 1975. The latter reference deals with the production and characteristics of Landsat 1 and 2 MSS computer compatible tapes. These materials were developed over a three year period and are used as a supplement to a two-hour slide illustrated lecture and workshop exercises given for training programs in geological remote sensing in the EROS Data Center.

DEVELOPMENT OF THE LANDSAT SYSTEM

The Landsat System was conceived by a group of scientists in the U. S. Department of Interior and the National Aeronautics and Space Administration (NASA). The exact date commemorating the development of the idea for a Landsat is difficult to ascertain because the ideas for such a system undoubtedly grew out of informal discussions over a period of years. The period of years spans the launch of the Nimbus weather satellites beginning in 1963 and probably ended in the late 1960's as the ERTS-Nimbus program was defined within NASA and the EROS Program was defined within Interior. One of the principal contributors to the concept of an earth resources technology satellite (ERTS) was Dr. William A. Fischer, now Senior Scientist for the Earth Resources Observation Systems (EROS) Program. Dr. Fischer and other U. S. Geological Survey geologists presented their ideas to the late Dr. William T. Pecora when he was Director of the Survey. When Dr. Pecora became Under Secretary for Interior, he took the lead in the

implementation of a satellite resources observations program within the Department of Interior.

The first satellite, called ERTS-A, used a Nimbus weather satellite platform which was modified to carry two sensor systems and a data relay system. The satellite was launched by a Thor-Delta rocket on July 23, 1972 from the NASA Western Test Range in Lompoc, California. The total weight of the launch vehicle was 133,400Kg and the total weight of the satellite was 815 Kg. When the satellite achieved orbit it was designated ERTS-1.

A second satellite called ERTS-B was developed as a follow-on experiment to ERTS-1. Because tape recorder problems prevented the use of one sensor on ERTS-1 it was decided to launch ERTS-B with the same sensor package as ERTS-1. Decisions related to the sensor package for ERTS-B and the exceptional performance of the Multispectral Scanning instrument on ERTS-1 delayed the launch of ERTS-B until January 22, 1975. When ERTS-B achieved orbit it was named Landsat 2 by officials in NASA, and ERTS-1 was renamed Landsat 1. The satellite program was renamed the Landsat Program in January 1975 to allow it to be distinguished from a planned oceanographic satellite program called Seasat.

In 1975 funding was approved for a third experimental earth observations satellite called Landsat-C. Landsat-C has a scheduled launch of Spring 1978 and the sensor systems in Landsat-C are somewhat different than in the first two satellites.

Landsat 1 and 2 data is now being used operationally by a wide range of users in government and industry and there is great pressure to transfer status of the Landsat program from an experimental to operational mode.

Funding has now been approved for the launch of a fourth satellite called Landsat-D. Landsat-D launch is scheduled for 1981 but at the present time NASA and the Department of Interior are defining the mission characteristics, data collection instrumentation, and data handling instrumentation in the light of developing user requirements.

SENSING PLATFORM CHARACTERISTICS

The Nimbus weather satellite platform designed over 15 years ago is the platform used for Landsats 1, 2, and the planned third satellite (Figure 1). The satellite is 3 meters high, 1.5 meters in diameter at

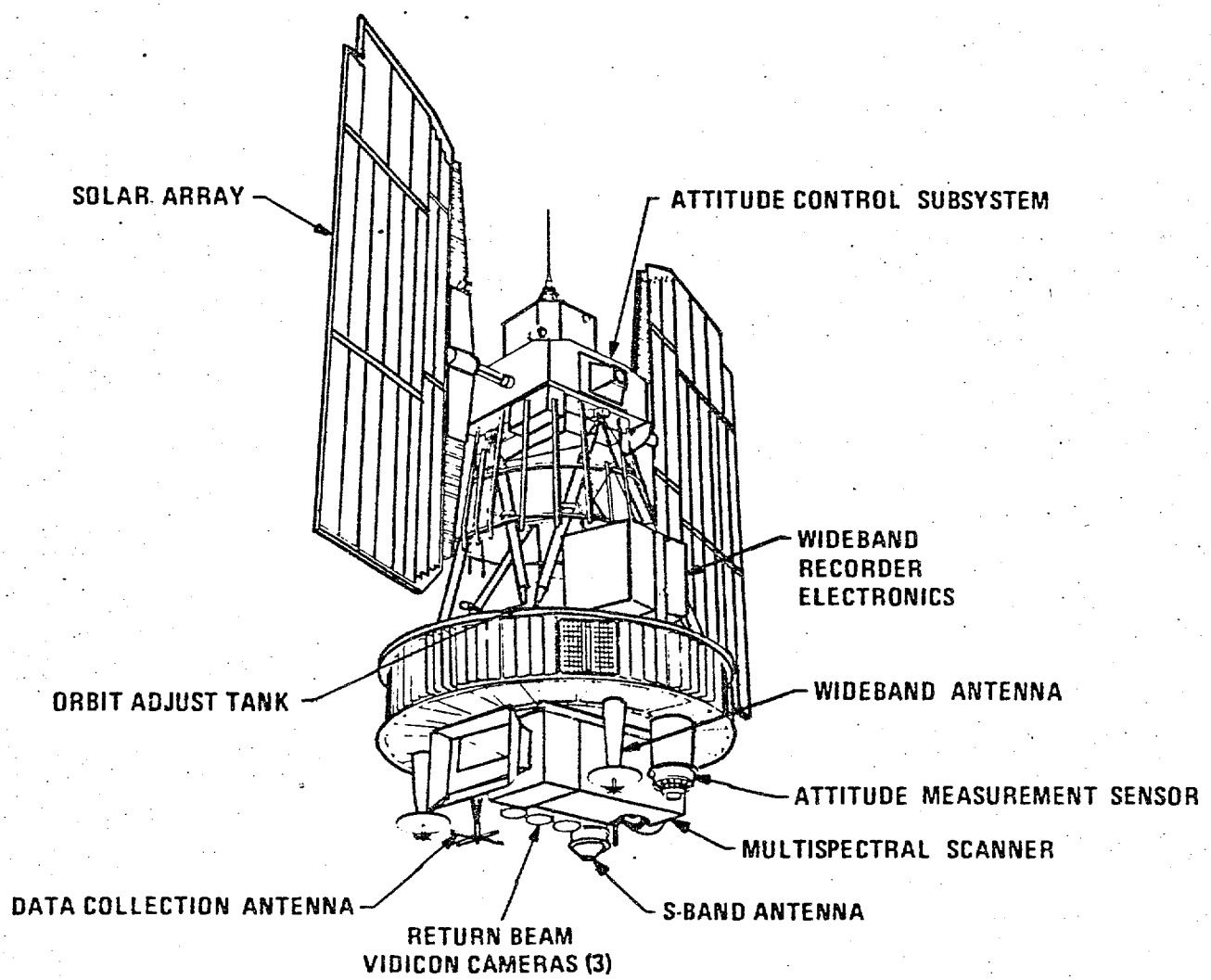

Figure 1. Nimbus platform for Landsat satellite. From NASA Landsat Data Users Handbook.

the sensor ring, and is 4 meters wide with the solar panels extended.

ORBIT CHARACTERISTICS OF LANDSATS 1 AND 2

SUN SYNCHRONOUS ORBIT

Landsat satellites are launched into a near-polar orbit at an altitude of approximately 900 Km. The orbital altitude varies between 880 Km and 940 Km, (Table 1)

TABLE 1

Orbit Parameter	Actual Orbit	Model Orbit
Semi-major axis	7285.82 Km	
Inclination	99.114 deg	99.092 deg
Period	103.267 min	103.267 min
Eccentricity	.0006	
Time of equatorial crossing	9:42 AM	
Coverage cycle	18 days	
Duration of cycle	251 revs	
Distance between adjacent tracks at the equator	159.38 Km	
Distance between sucessive tracks at the equator	2760 Km	
Altitude	880 - 940 Km	918.592 Km

Table 1. Characteristics of the Landsat orbit.

The orbit of the Landsat satellites is sun synchronous (figure 2). The The angle between the sun, center of the Earth and the satellite is maintained at 37.5 degrees as the Earth orbits the sun, and the orbital plane of the satellite is inclined 99 degrees, measured clockwise from

the equator (figure 3). This type of orbital configuration insures repeatable

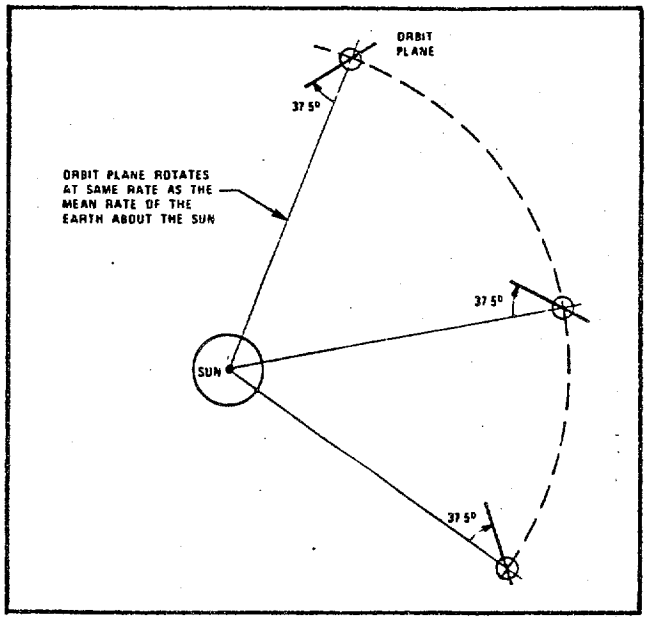

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Figure 2. Sun synchronous Landsat orbit. From NASA Data Users Handbook.

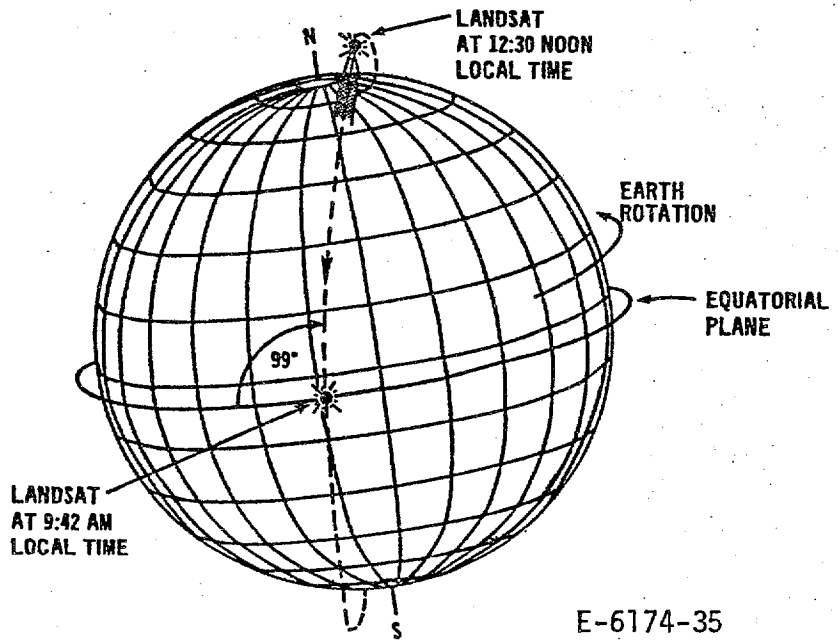

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Figure 3. Inclination of Landsat orbit to maintain sun synchronous Landsat orbit.

sun illumination conditions. Repeatable illumination conditions are necessary for mosaicking of adjacent tracks tracks of imagery and for comparison of yearly changes in landscape cover.

The satellite crosses the equator every 103 minutes. In 103 minutes the Earth rotates a distance of 2760 Km under the satellite at the equator. If the first satellite overpass comes down over the New York area in the eastern United States, the next overpass would be close to Sioux Falls, South Dakota (Figure 4). When the satellite makes 14 orbits, 24 hours elapse, and the next westward track of data is acquired (Figure 4). In 18

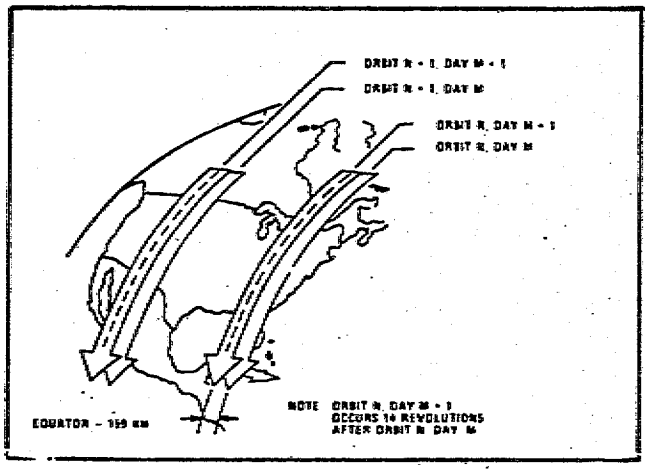

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Figure 4. Orbital coverage characteristics of Landsat. From NASA Data Users Handbook.

days one satellite will be able to obtain repeat coverage of the Earth's surface, providing weather conditions permit and the satellite sensing systems are turned on (Figure 5). The satellite crosses over the north pole about 3 PM (1500 hours) local time. As the satellite travels southward, gathering data on the sunlit side of the Earth, it crosses Alaska about 10 AM, and then the equator at 9:42 AM local time. As the

satellite continues southward it crosses Chile at 9:00 AM and the south pole at 3:00 AM local time (Figure 6).

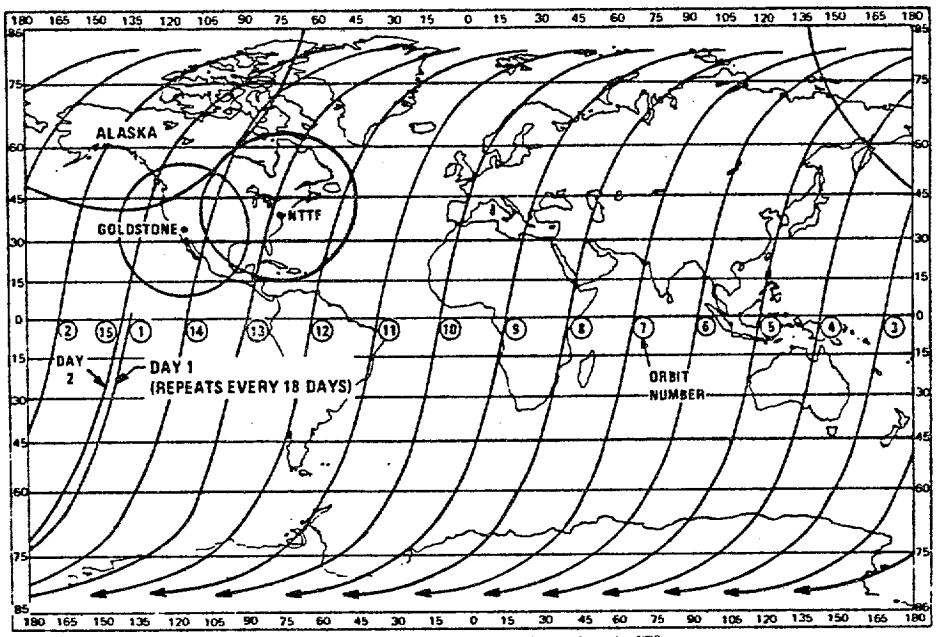

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Figure 5. Landsat orbital tracks for one day of coverage. (From NASA Data Users Handbook).

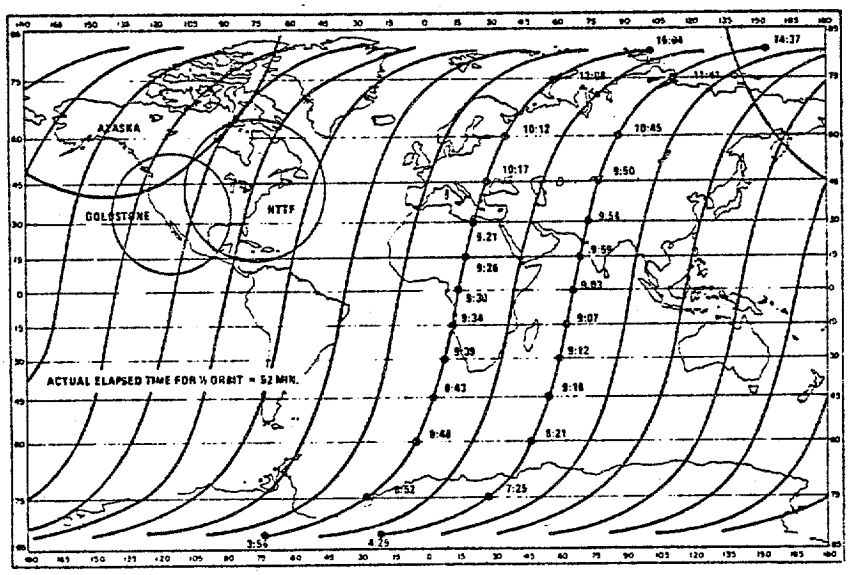

Figure 6. Variations in local time of data acquisition. From NASA Landsat Data Users Handbook.

Landsat 2 was launched so that it would follow Landsat 1 by 9 days in orbit. Therefore with the two satellites, 9 day coverage of the Earth, between 82°N and 82°S latitude,was possible providing the weather permitted observations and the satellites' instruments were turned on.

VARIATIONS IN SOLAR ILLUMINATION

Landsat has a sun synchronous orbit which insures repeatable illumination conditions. This does not mean that illumination conditions are uniform along a Landsat ground track, or that they are unchangeable throughout the year. In the Sioux Falls area the Sun's rays strike the Earth at angles close to 20° in December and in July they strike the earth at 60° angles. Solar elevation angle relationships are shown in Figure 7.

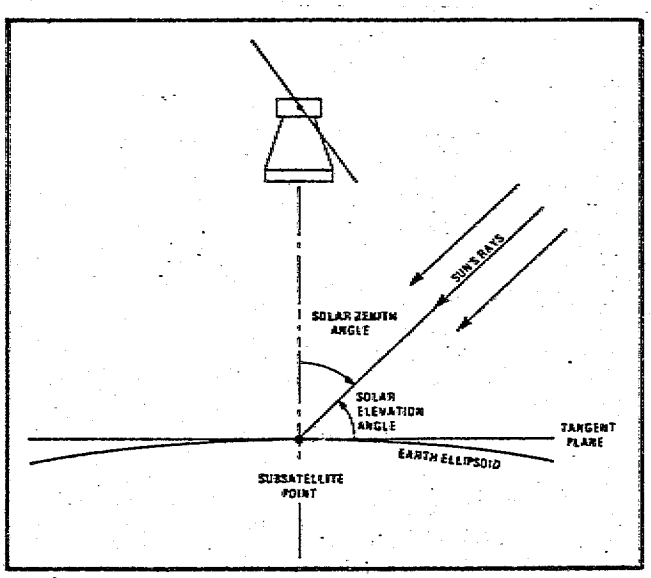

Figure 7. Sun illumination relationships. From NASA Landsat Data Users Handbook.

Along a single satellite ground track acquired in January, the solar elevation angle was observed to change from 4° in Alaska to 45° near the equator. Optimum sun angles for landform and drainage analysis in

terrain of moderate relief, are close to 25°. In mountainous terrain cover conditions are best analyzed with the data acquired with the highest possible sun angle to minimize topographic shadowing. Low solar illumination is desirable for flat, highly reflective, desert terrain. Relationships between latitude of satellite data acquisition, solar elevation angle, and time of year of data acquisition are shown in Figure 8.

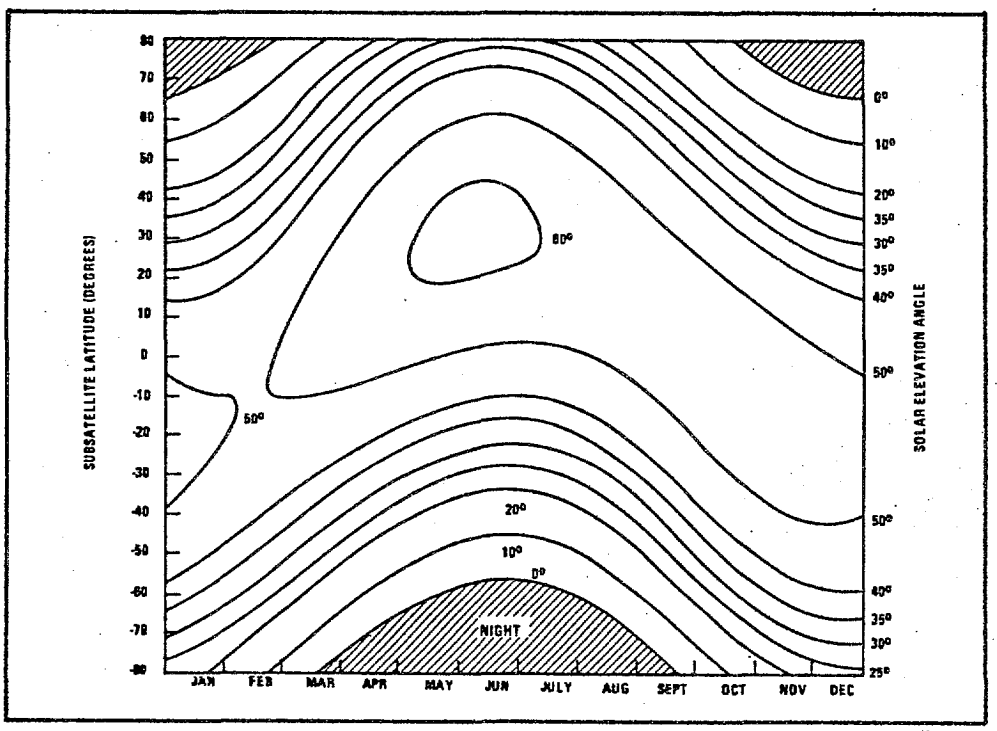

Figure 8. Solar elevation angles at different latitudes and different times of year for the Landsat satellite. NASA Landsat Data Users handbook.

The azimuth of solar illumination also changes with season and latitude (Figure 9). Different directions of solar illumination cause different illumination conditions for terrain features of the Earth's surface. These relationships can influence an analysis and interpretation of landscape features, particularly topographic lineaments (Taranik and Trautwein, 1977, p. 775).

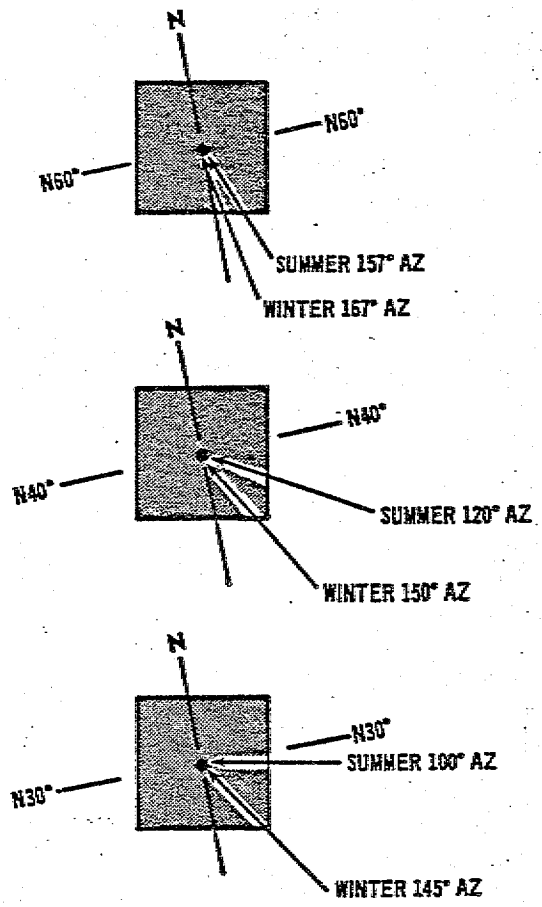

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Figure 9. Variations in azimuth of solar illumination with season and latitude.

ORBIT STABILIZATION

Landsat satellites are stabilized for pitch, yaw and roll by a system of flywheels and rate gyros. This type of stabilization maintains the attitude of the satellites with respect to the Earth's surface. The satellite orbits are configured to offset the gravitational forces of the Earth - Moon - Sun system, however some orbital precession does occur and the orbit must be adjusted every several months so there will be nominal repetetive coverage within each ground swath. These adjustments are accomplished with a gas reaction jet system. Orbital precession and

variations in satellite attitude cause variations in the area covered by repetitive overpasses (Figure 10). The altitude of the satellite also

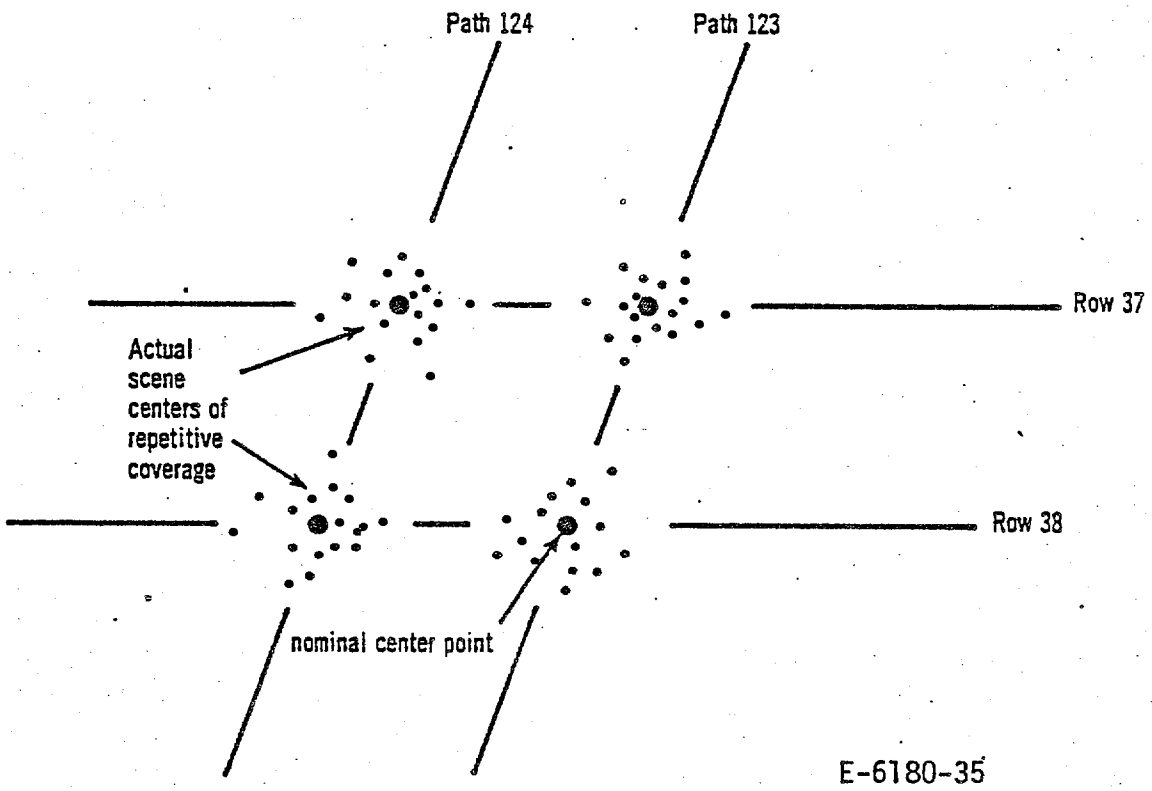


Figure 10. Relatioship of actual scene centers to nominal center points for Landsat scenes acquired on a repetitive basis.

varies between 880 and 940 Km and this introduces variations in the scale of the data. These geometric distortions must be compensated for if Landsat data are to be registered.(see Taranik, 1977 for a discussion of registration of Landsat data).

The orbit of Landsat 1 could no longer be stabilized by the gas reaction jet system in 1976 and it was allowed to continue precession until it again coincided with the orbit of Landsat 2. This procedure

resulted in an earlier equatorial crossing time for Landsat 1 and caused repetitive coverage using the two satellites to occur at 6 and 12 day intervals. The earlier equatorial crossing time for Landsat 1 means that much lower sun angles of illumination were available beginning in Spring of 1977. These new low sun illumination angles should allow better analysis of areas having low topographic relief.

SIDELAP IN LANDSAT COVERAGE

Because orbital tracks of the satellite coincide at the poles and diverge at the equator, the amount of sidelap between adjacent ground swaths varies from over 60% in Alaska, to 35% in South Dakota, and to only 14% at the equator (Figures 11, 12, and 13). Where there is sufficient sidelap and sufficient topographic relief (usually 200 m or more) Landsat imagery can be analyzed using the relief displacement present in the data and stereoscopic viewing (Welch and Lo, 1977).

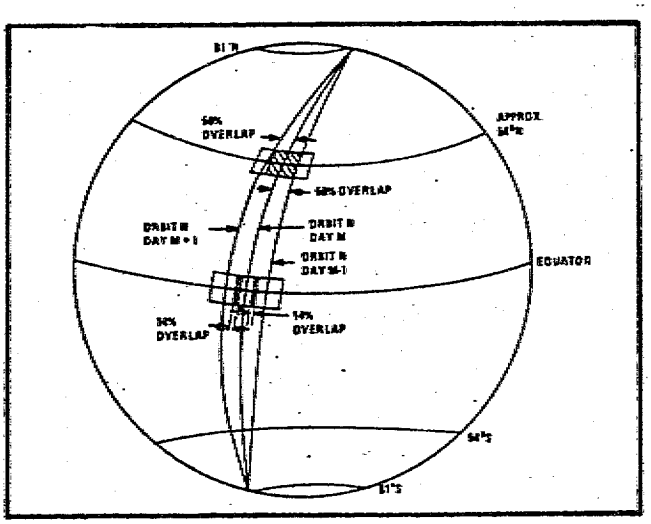


Figure 11. Orbital coverage of adjacent tracks. NASA Landsat Data Users Handbook.

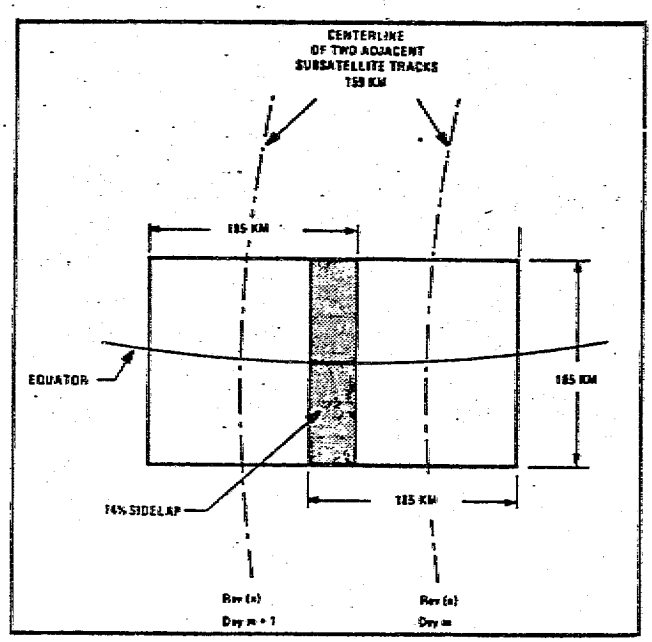


Figure 12. Sidelap between adjacent Landsat images at the equator. NASA Landsat Data Users Handbook.

Latitude (deg)	Image Sidelap (%)
0	14.0
10	15.4
20	19.1
30	25.6
40	34.1
50	44.8
60	57.0
70	70.6
80	85.0

Figure 13. Relationships between latitude of data acquisition and image sidelap.

IMPORTANCE OF REPETITIVE COVERAGE FOR GEOLOGIC APPLICATIONS

Prior to the launch of the Landsat satellites, repetitive coverage was thought by many to be unnecessary for most geologic applications. The geology does not change much between repetitive satellite overpasses, however the landscape cover conditions can change considerably with the seasons, and even over periods of several years. The importance of repetitive coverage for geologic investigations is best illustrated by recent studies of Pleistocene materials and landforms in the upper Midwest. Staff of the Iowa Geological Survey first began to investigate the utility of mapping Quaternary landscape features with the U. S. Geological Survey in 1972. In the first year of the investigation the only cloud free coverage of the portions of Iowa being examined occurred in July and August of 1972. The investigators reported the Landsat data appeared to be of limited value in the mapping of Quaternary relationships in Iowa based on analysis and interpretation of the summer imagery. Later Morrison (1976) found that early June imagery acquired in 1973 appeared to display interesting landscape features in the Des Moines area that were related to the last advance and retreat of continental glaciers from Iowa. In the period 1974 through 1976

a team of investigators from the University of Iowa and the EROS Data Center began evaluating seasonal coverage of northwestern Iowa with Landsat imagery. Month by month coverage of northwestern Iowa was not possible until four years of Landsat data were acquired by two satellites. Complete coverage on a month by month basis, would not have been possible until Late 1977 with one satellite. Coverage in the area was dictated by weather conditions which frequently caused clouds to be present in the areas being examined. On the basis of analysis of the seasonal coverage Lucas and Taranik (1977) found that late April-early May imagery provided the best display of Quaternary materials and landforms in the upper Midwest. Many landscape features produced by continental glaciation are of dimensions that require several Landsat images to properly display them. A regional mosaic of late April - early May imagery was started in 1975 but it could not be completed until late 1976. This mosaic contained images acquired over a 5 year period by two different Landsat satellites. In many areas only one acceptable frame of imagery was produced during 5 years of coverage by two satellites (Lucas and Taranik, 1977).

Many geological problems require analysis of imagery from several different seasons. Imagery acquired in December is useful for landform and drainage analysis. In arid environments springtime imagery may provide important groundwater and surfacewater information from the analysis and interpretation of vegetation cover patterns. A comprehensive geological analysis of the hydrogeology of the Tucson area required imagery from two different seasons (Taranik and Trautwein, 1977).

LANDSAT 1 AND 2 PAYLOAD

The satellite payload for Landsats 1 and 2 consists of two data collection instruments called the Multispectral Scanner (MSS) and the Return Beam Vidicon (RBV), the Data Collection System (DCS) relay antenna, and two Wide Band Video Tape Recorders (WBVTR'S), (Figure 14). The total

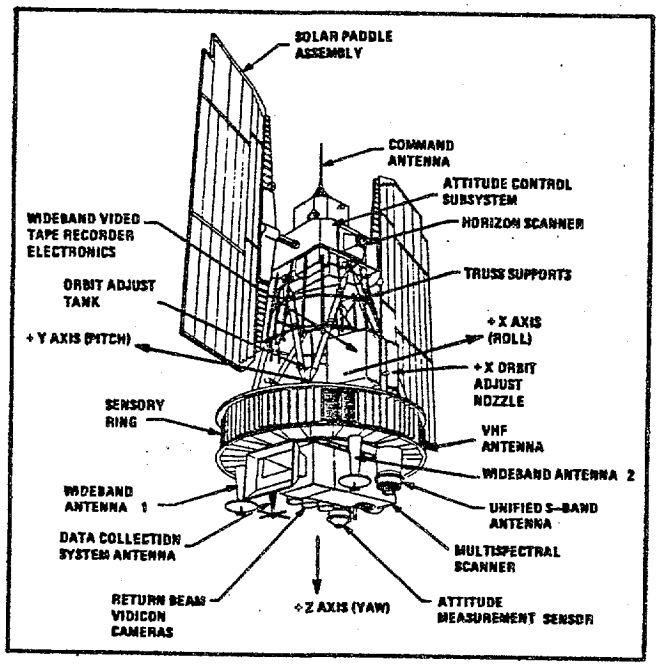


Figure 14. Payload for Landsats 1 and 2.
From NASA Landsat Data Users Handbook

weight of the payload is 240 Kg. Because of problems with the tape recorders on Landsat's 1 and 2, little RBV data is available or has been used for mineral and petroleum expolration. The RBV system is discussed under Landsat-C payload. The Data Collection System (DCS) is primarily a real-time data relay system which can relay 8 separate ground measurements to Goddard Space Flight Center, every 12 hours, from a remote site. The DCS has been used to monitor volcanoes, hydrologic phenomena, and production platforms in the Gulf Coast, but has not been

used for purposes of mineral exploration. Persons with interest in this system should consult the NASA Landsat Data Users Handbook and the NASA Data Collection System Handbook for ERTS.

The spectral wavelength intervals (bandpasses) detected by the sensing systems on Landsats 1 and 2 are shown in Table 2.

TABLE 2

Data Channel	System	Type of Radiation	Wavelength	NASA Code
1	RBV	Visible, yellow-green	0.475-0.575μm	Band 1
2	RBV	Visible, green-red	0.580-0.680μm	Band 2
3	RBV	Visible red-invisible IR	0.690-0.830μm	Band 3
1	MSS	Visible green	0.5 - 0.6μm	Band 4
2	MSS	Visible red	0.6 - 0.7μm	Band 5
3	MSS	Invisible reflected IR	0.7 - 0.8μm	Band 6
4	MSS	Invisible refelcted IR	0.8 - 1.1μm	Band 7
(5)	(MSS)	(Invisible thermal IR)	(10.2 -12.6μm)	(Band 8)1/

1/ Landsat-C MSS, channel not on Landsats 1 and 2

A diagram of the electromagnetic spectrum is shown in Figure 15 for reference.

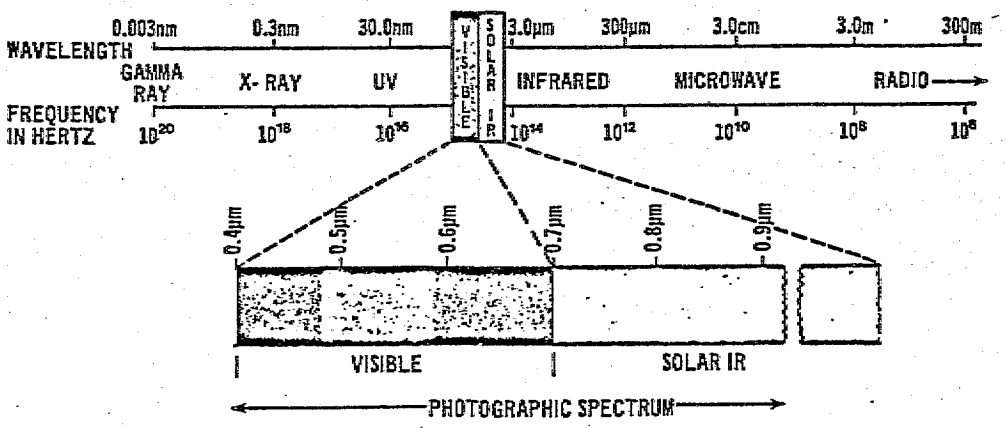


Figure 15. The electromagnetic spectrum with the visible range and reflected (solar infrared) range shown.

THE LANDSAT MULTISPECTRAL SCANNER

Function of the Multispectral Scanner

A schematic drawing of the MSS is shown in Figure 16. The MSS has

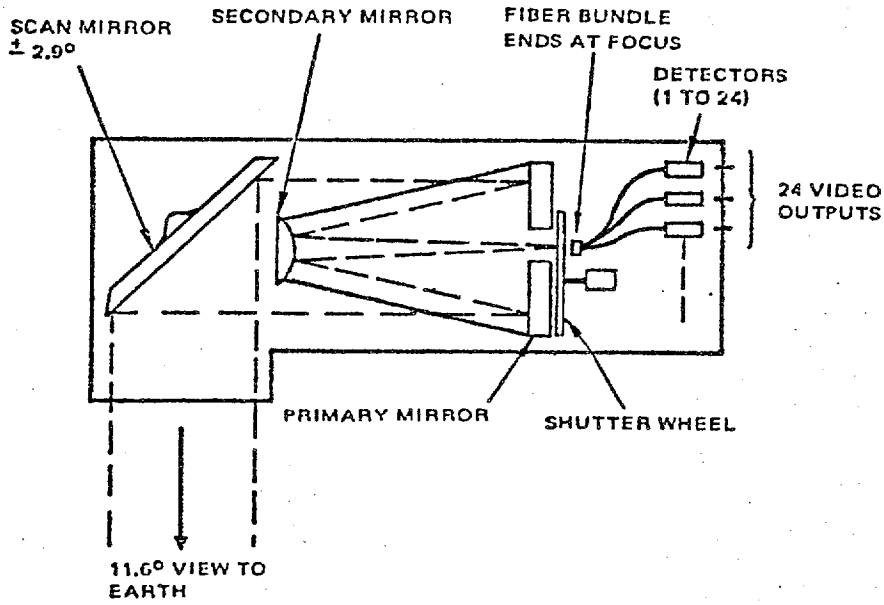


Figure 16. Schematic drawing of the MSS. From the final report on the MSS for ERTS, Hughes Aircraft.

an oscillating mirror which scans the Earth's surface from west to east. Radiation coming from the surface of the Earth is reflected by the mirror into reflecting telescope optics which focus the radiation on fiber optic bundles located in the focal plane of the telescope. The configuration and size of the fiber optic bundles determines the ground instantaneous field of view of the sensor (Figure 17). Radiation is conducted by the fiber optic light pipes to filters which allow only certain wavelengths of radiation to strike the detectors. A voltage is produced by each detector which is related to the amount of radiation reaching the detector. Each detector is capable of producing voltages which range from zero to five volts, however only a 4 volt range is utilized.

Two gain modes are utilized with the MSS (Figures 18 and 19). The

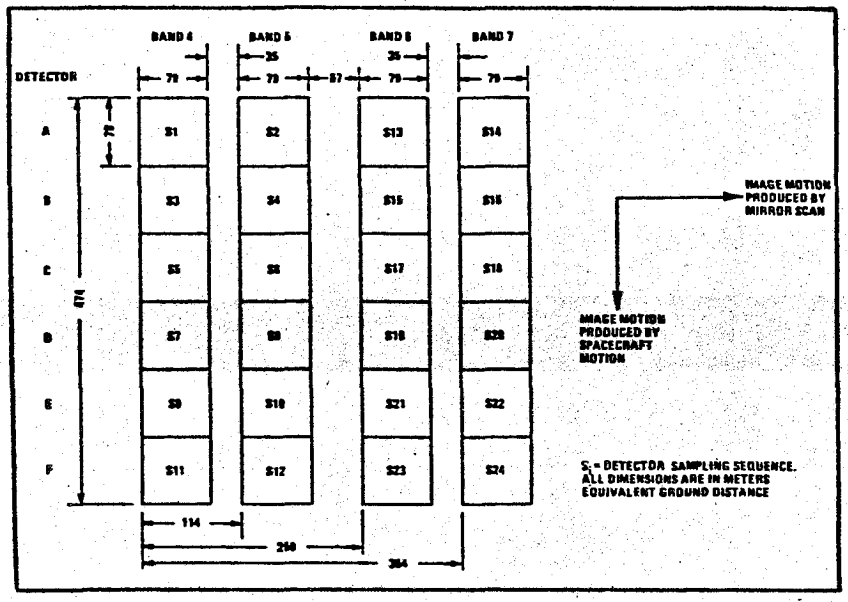


Figure 17. Geometry and ground dimensions of fiber optic bundles at focal plane in MSS telescope. NASA Landsat Data Users Handbook.

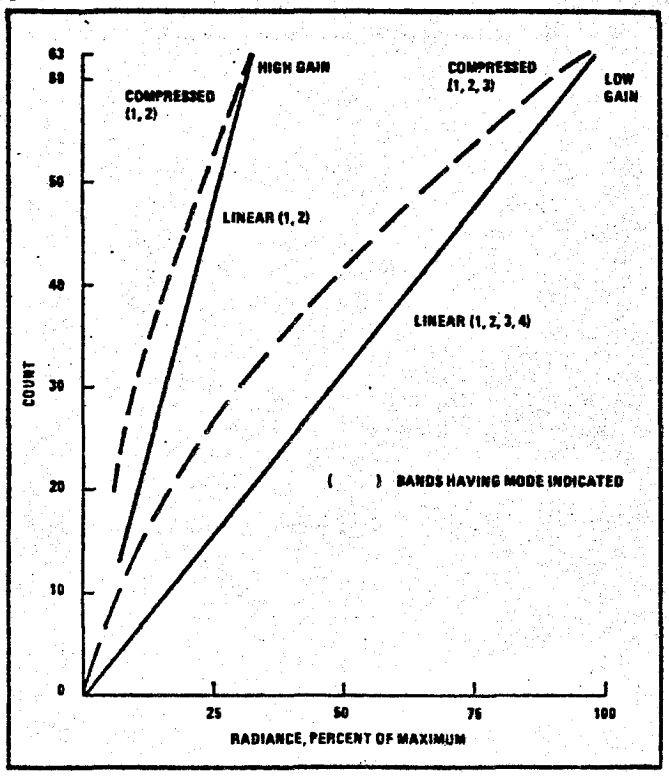


Figure 18. Relationship between maximum percent of radiance and digital count for MSS. NASA Landsat Data Users Handbook.

Maximum Radiance (milliwatts/cm^2–SR)

Band	Low Gain	High Gain
1	2.48	0.83
2	2.00	0.67
3	1.76	–
4	4.60	–

Figure 19. Maximum radiance for low and and high gain for the MSS. NASA Landsat Data Users Handbook

low gain mode is used mostly over land surfaces and the high gain mode is sometimes used over water surfaces. The gain is changed only by ground command. The voltage produced is an analog signal which is converted to a digital number ranging from zero to 63 by a multiplexer. The digital number represents a brightness value (BV) related to the true brightness on an area on the Earth's surface in one wavelength band (Figures 20 and 21).

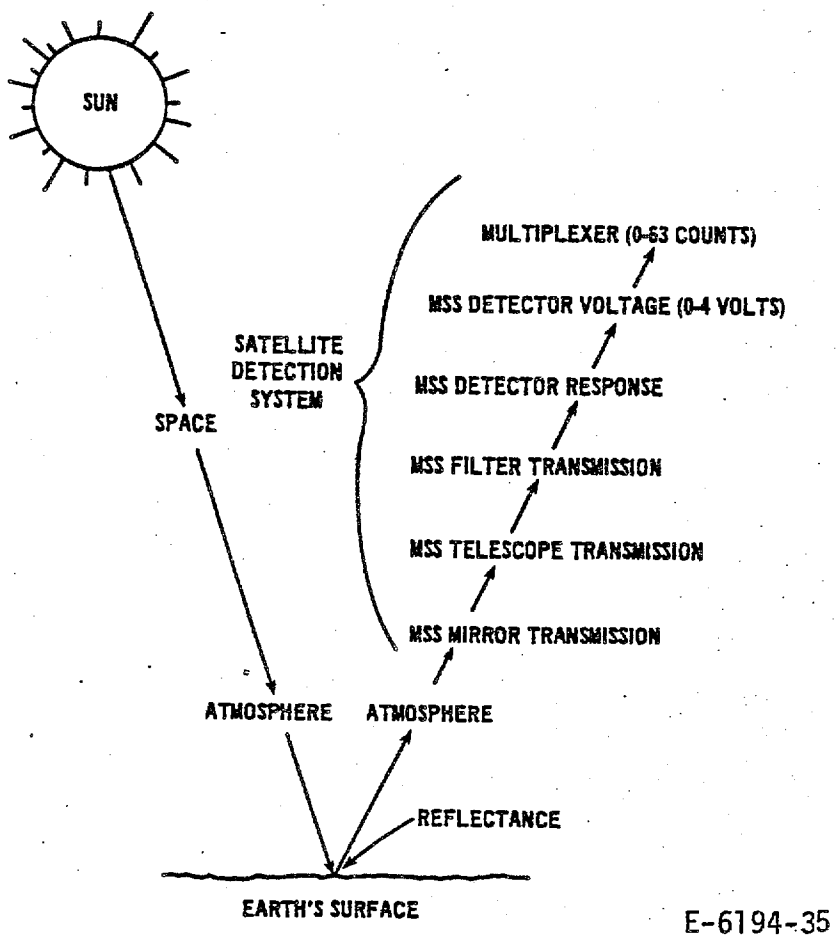


Figure 20. Energy path for Landsats 1 and 2.

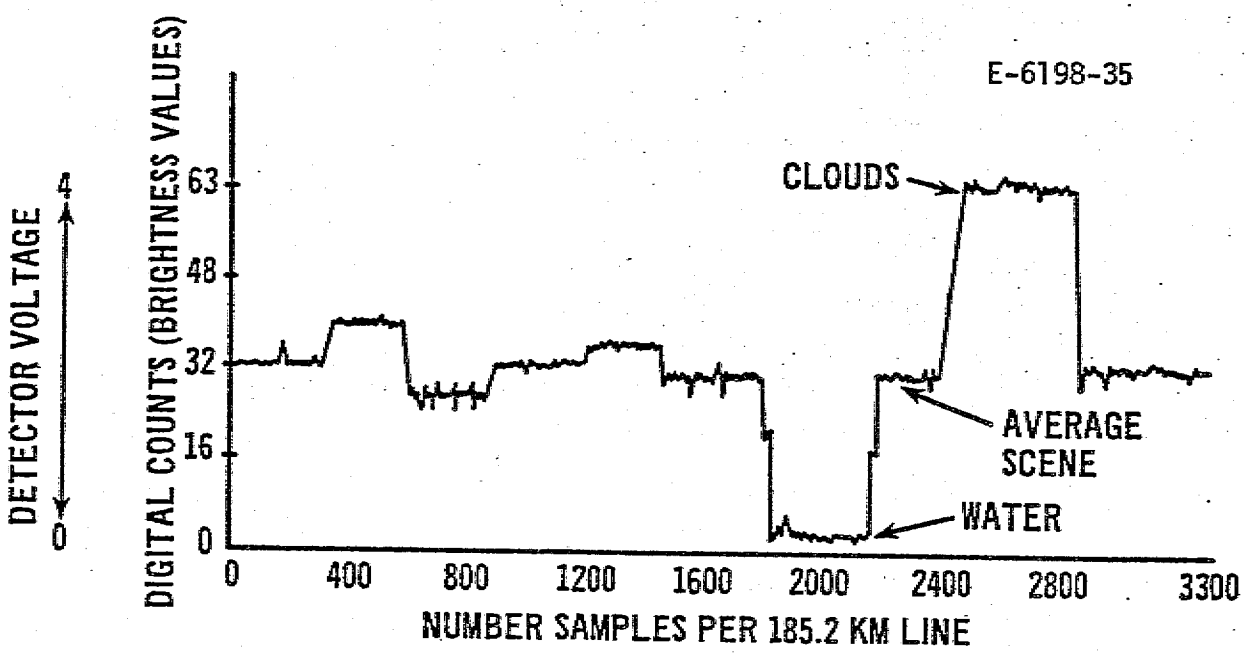


Figure 21. Relationship between scene brightness, voltage and digital count. From Ragland and Chavez, 1976.

The Multispectral scanner scans six lines of data at a time (Figure 22).

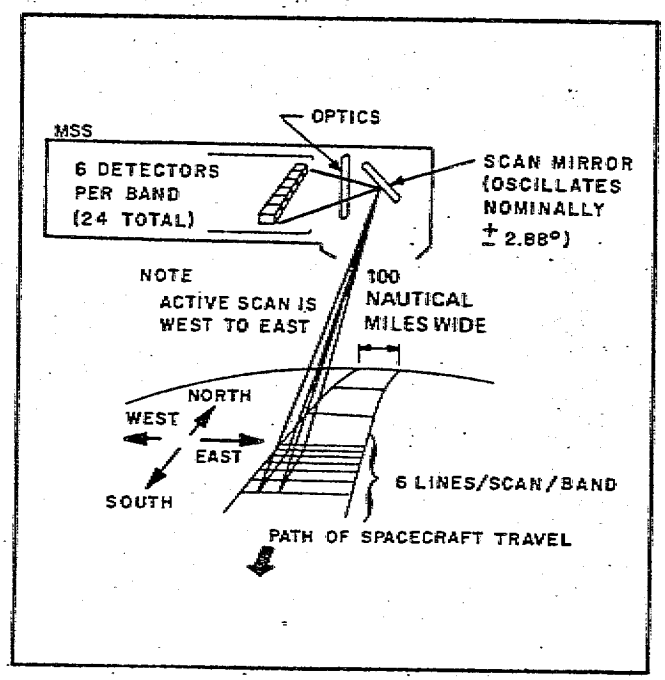


Figure 22. Scanning arrangement of the MSS. From NASA Landsat Data Users Handbook.

Each scan line is about 185.2 Km long on the ground. The Earth is scanned from west to east in approximately 33 milliseconds (The mirror oscillates

at 13.62 Hertz). During the retrace cycle of the mirror a shutter blocks out the energy from the Earth and the detectors are exposed to internal and sun calibration sources. Because six lines of data are scanned at one time and radiation is divided into four wavelength bands, 24 detectors are used in the MSS. The spacecraft moves south as the six lines are scanned so the scan lines are not perpendicular to the line of flight (Figure 23).

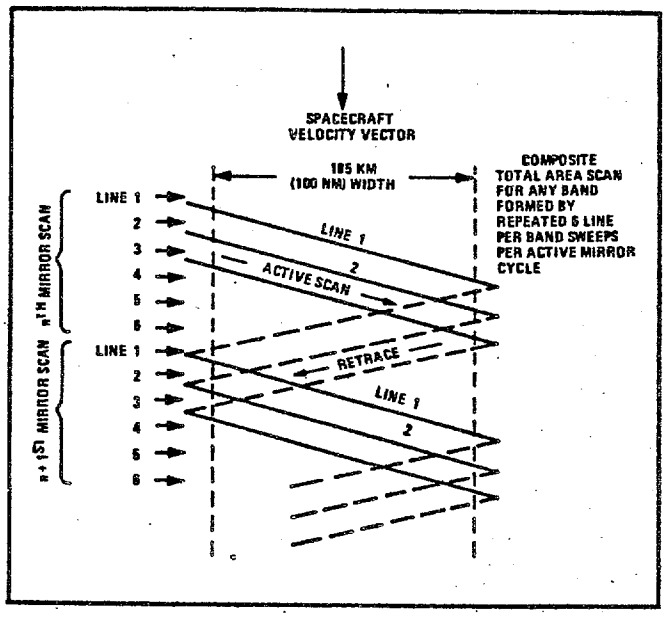
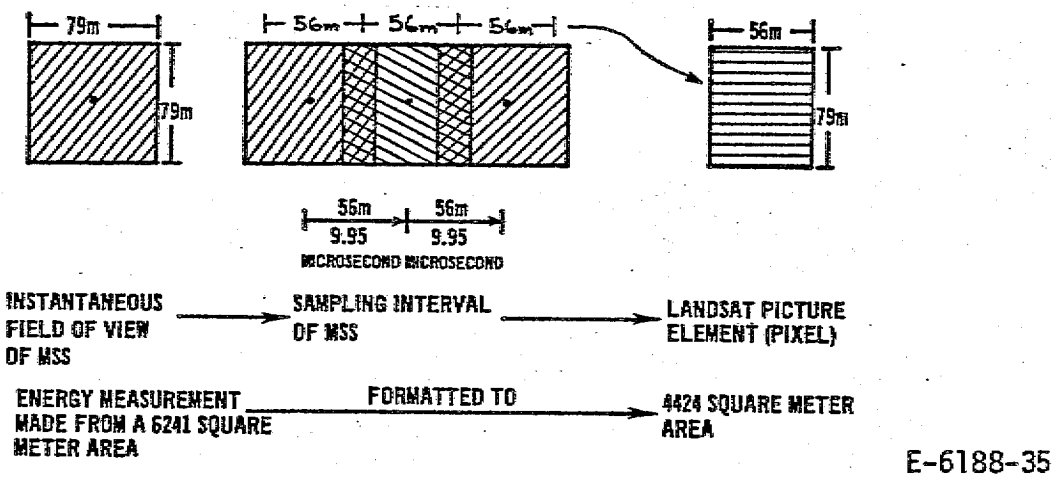


Figure 23. Scanning pattern of the MSS on the Earth's surface. NASA Landsat Data Users Handbook

Formation of the MSS Picture Element

During each west to east scan the voltage produced by each detector is sampled every 9.95 microsecond. For one detector, approximately 3300 samples are taken along a 185.2 Km line (Figure 21). By division the instantaneous field of view of 79 m by 79 m must move a distance

close to 56 m on the ground between each sample (Figure 24). The individual



E-6188-35

Figure 24. Formation of the MSS picture element (PIXEL).

radiation measurements from the IFOV must be arranged on an image in a manner that preserves spatial relationships. Thus the measurements must be assigned an area of dimensions 56 m by 79 m on imagery or geometric distortions will be introduced. The 56 m by 79 m area is called a Landsat picture element or pixel. The measurement of landscape brightness is made from a 6241 square meter area, but the data are formatted as if the measurement were made from a 4424 square meter area (Figure 24). Note the overlap of the areas from which measurements of brightness were made for adjacent pixels (Figure 24).

Detection of Ground Features With the MSS

The detection of ground features by the Landsat MSS is shown in Figure 25. The detection of ground features is dependent upon the relationships between the brightness of the feature and its size, with respect to the brightness of the background against which the feature is imaged. The instantaneous field of view (IFOV) of the MSS integrates

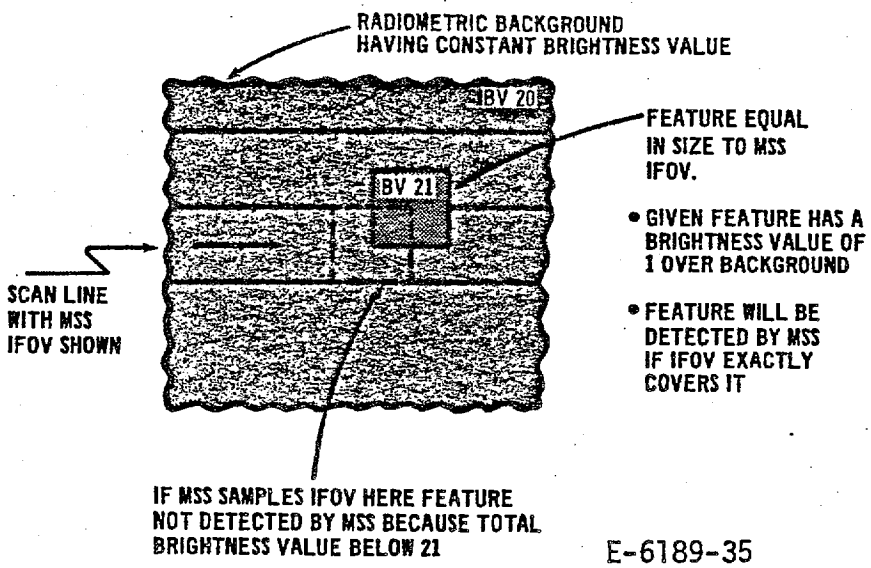
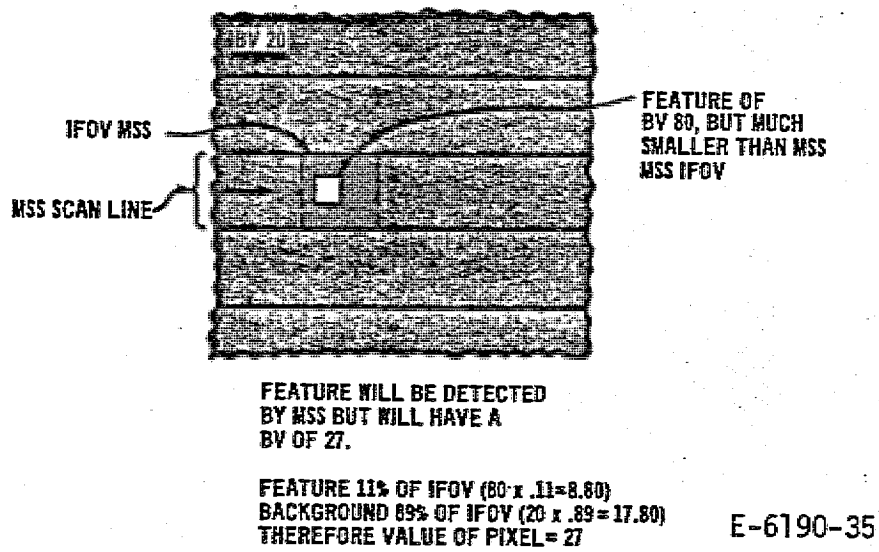


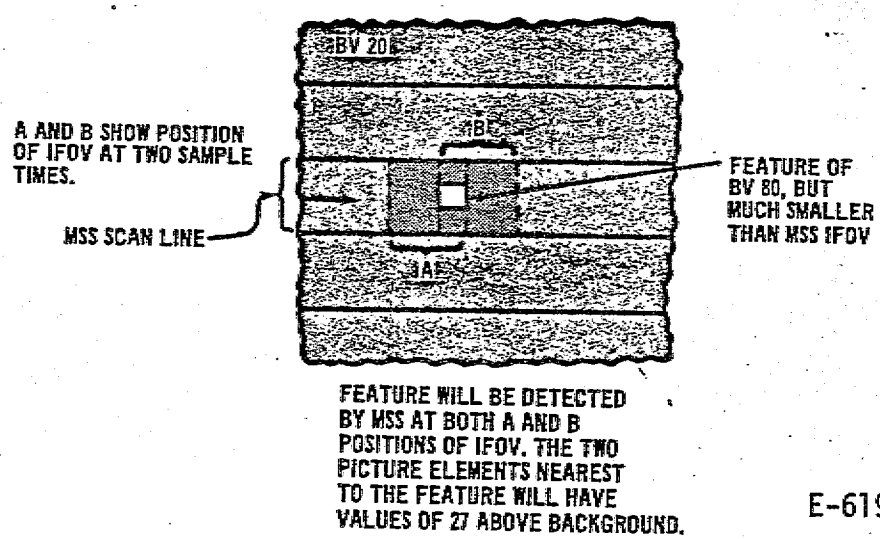
Figure 25. Detection of ground features with the MSS on Landsats 1 and 2 - Case 1

the brightness of all landscape cover within an area of about the size of a football field. If there is a difference in brightness of one between the background and a feature equal to the size of the IFOV, then the IFOV must exactly fit over the feature when the detector voltage is sampled, if the feature is to be detected by the MSS (Figure 25). This is rarely the case and usually the IFOV is sampled when it covers only a part of the feature (Figure 25). In this latter case the feature will not be detected. If the feature with a brightness of one over background is any smaller than the IFOV it will not be detected when the voltage produced by the detector is sampled, even though the IFOV completely covers the feature. Features which are smaller then the IFOV can be detected by the MSS if their brightness is sufficient to give a total brightness of 1 over background (Figure 26). If a feature smaller than the IFOV lies in the overlap area common to adjacent pixels it is possible for the feature to influence the brightness of two picture elements, if it has sufficient brightness (Figure 27).



E-6190-35

Figure 26. Detection of ground features by the MSS on Landsat - Case 2.



E-6191-35

Figure 27. Detection of ground features by the MSS on Landsat - Case 3.

Depending upon the spectral characteristics of features and the background against which they are imaged, features detected in one spectral band may not be detected in another spectral band.

A spatial array of picture elements and their values for one Landsat band is shown in Figure 28. Two roads of brightness value 80 cut diagonally across a background of brightness value 20. If all the pixels influenced by brightness from roads were shaded, the patterns would no longer be straight and continuous but would appear as rectangular segments. No pixels in the array have a brightness value of 80 because the roads are much smaller than the IFOV.

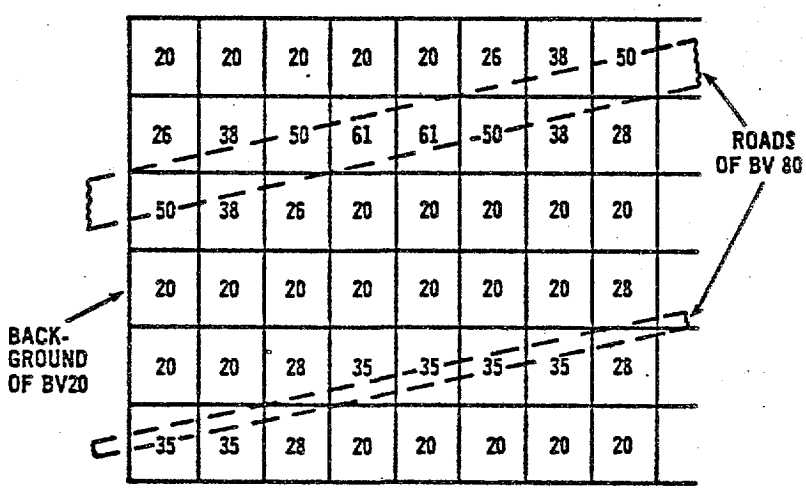


Figure 28. Spatial array of pixels from a portion of one Landsat band with values shown.

Integration of Ground Spectral Response

If red sandstone and green vegetation were present in equal amounts in an area sampled by the MSS, the resulting spectral signature would not resemble the signature for vegetation or the signature for red sandstone (Figure 29). The combined spectral signature is an average of the spectral signatures for the two cover types in the IFOV. The

signature shown in Figure 28 ignores the effects of the atmosphere between the ground and the satellite. The area sampled by the Landsat MSS is about the size of a football field and thus there is always an excellent probability that vegetation, soils, unconsolidated material, and cultural features will influence the measurement of spectral characteristics of rock units. One of the most important considerations

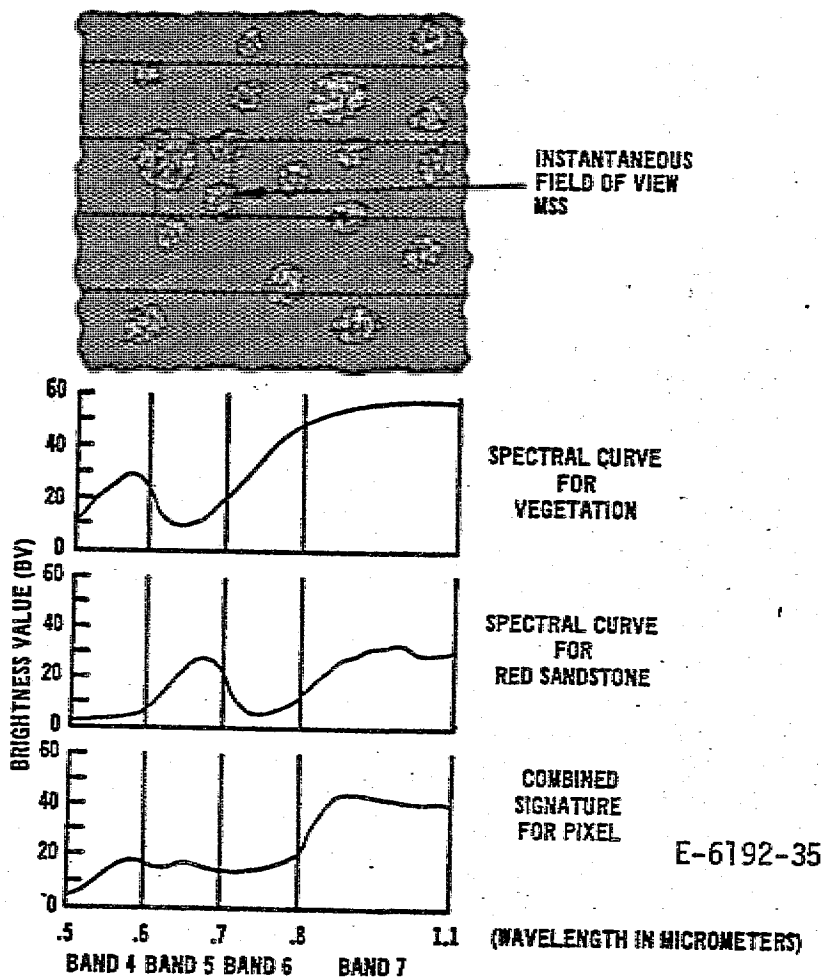


Figure 28. Integration of spectral response by the Landsat MSS. Atmospheric effects not considered.

in making comparisons between ground-based observations of geologic phenomena (alteration zones, lithology, etc.) and Landsat satellite data is an understanding of what cover conditions exist in the area

being sampled by the MSS. The fact that the MSS integrates spectral characteristics of the landscape from football field sized areas, instead of making discrete spectral measurements from individual cover types, might appear to be a serious limitation of Landsat data. In some situations and applications size of the IFOV of the MSS is a serious problem. However, some cover conditions develop in response to the geology and often the combination of soils, soil moisture, vegetation, etc., produce an anomalous signature which might be otherwise overlooked by a ground based scientist who gathered discrete spectral measurements from individual cover types.

Effects of the Atmosphere On Landscape Spectral Brightness

Solar radiation is largely unaffected as it travels through space, but it is selectively scattered and absorbed by the Earth's atmosphere (Figure 29). The atmosphere scatters green (band 4) wavelengths of

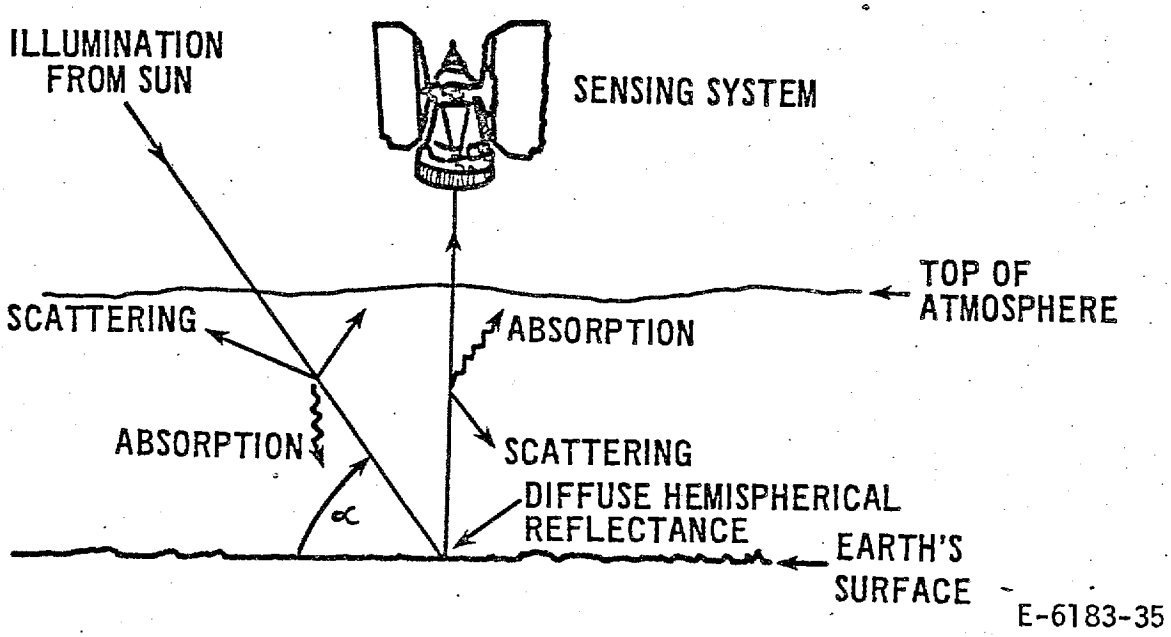


Figure 29. Atmospheric effects on the energy path between the sun and the Landsat satellite.

solar radiation four times more than infrared (band 6) radiation of longer wavelength (Figures 30 and 31). Atmospheric absorption which

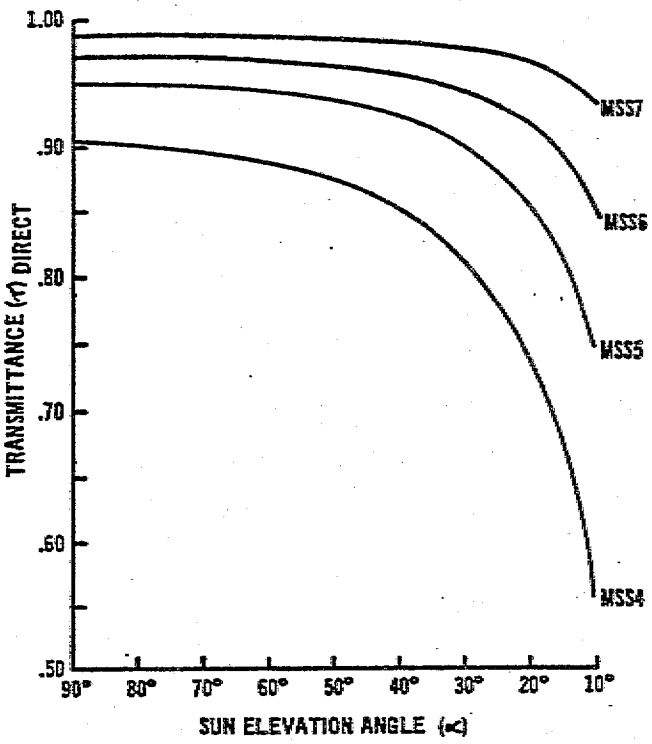


Figure 30. Effect of molecular scattering (rayleigh) and sun angle on radiation transmitted to Earth's surface. Data from Trautwein, personal communication.

E-6184-35

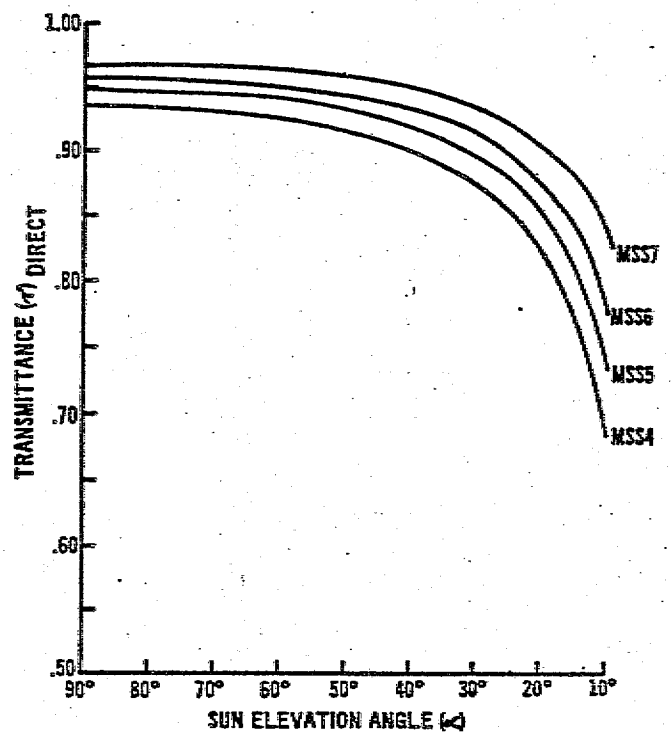


Figure 31. Effect of aerosol scattering (Mie) and sun angle on radiation transmitted to Earth's surface. Data from Trautwein, personal comm.

E-6185-35

is largely a function of water vapor and other gases in the atmosphere, mostly affects radiation of wavelengths longer than 0.8 micrometer (band 7) (Figures 32 and 33). Atmospheric scattering adds a brightness while atmospheric absorption subtracts a brightness from landscape spectral brightness.

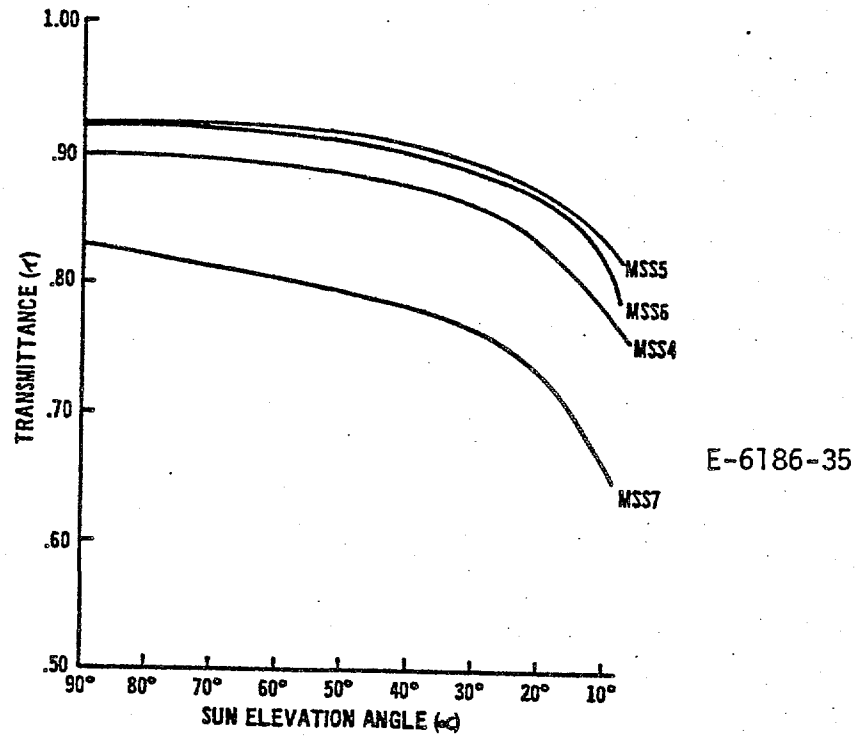


Figure 32. Effect of water vapor absorption and sun angle on solar radiation transmitted through the atmosphere to the Earth's surface(1 cm precipitable water). Data from Trautwein, personal communication.

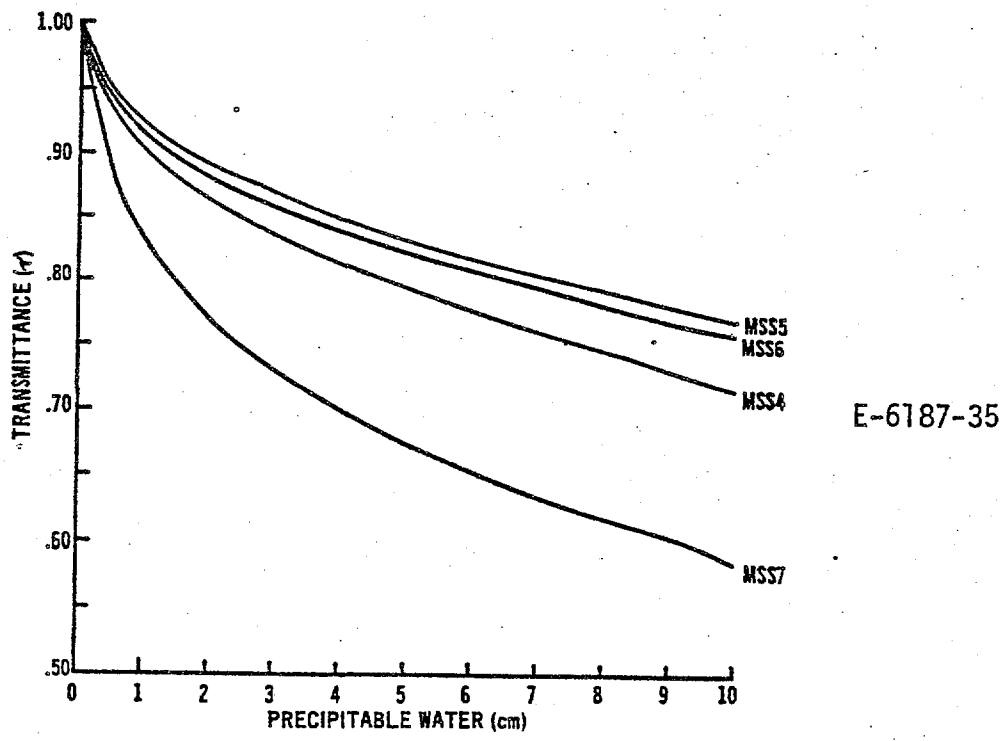
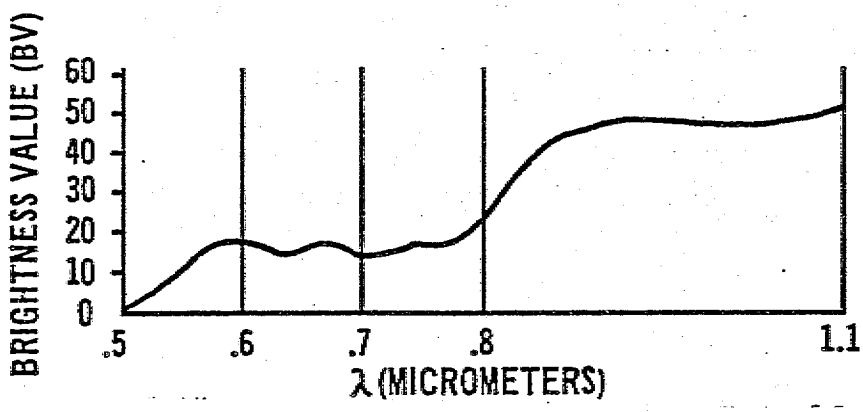


Figure 33. Effect of water vapor absorption on transmittance of Landscape brightness from Earth's surface to Landsat. Data from Trautwein, personal communication.

The integrated spectral brightness for a landscape covered with red sandstone and green vegetation is shown in Figure 34. The spectral



E-6193-35

Figure 34. Integrated spectral brightness for a landscape covered with red sandstone and green vegetation, assuming no atmosphere and equal proportions of the cover types.

brightness for that landscape, after the radiation has passed through the atmosphere is shown in Figure 35. The brightness of the landscape

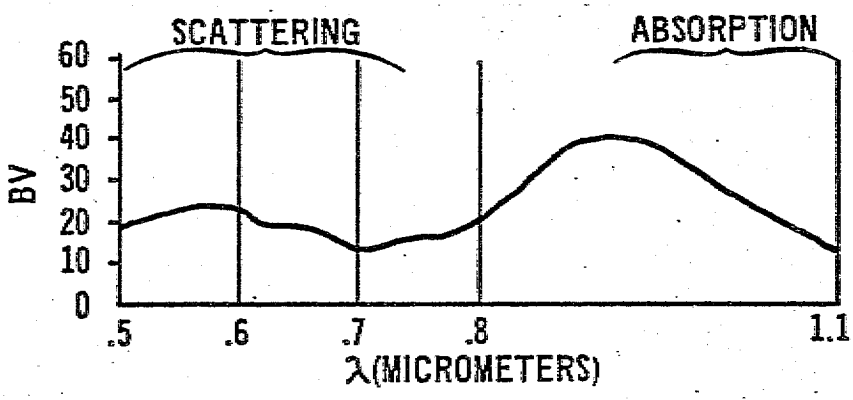


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Figure 35. Landscape brightness for an IFOV area of the MSS that is composed of equal amounts of red sandstone and green vegetation, after the radiation has passed through the atmosphere.

as spectrally recorded by the MSS is shown in Figure 35. The combination

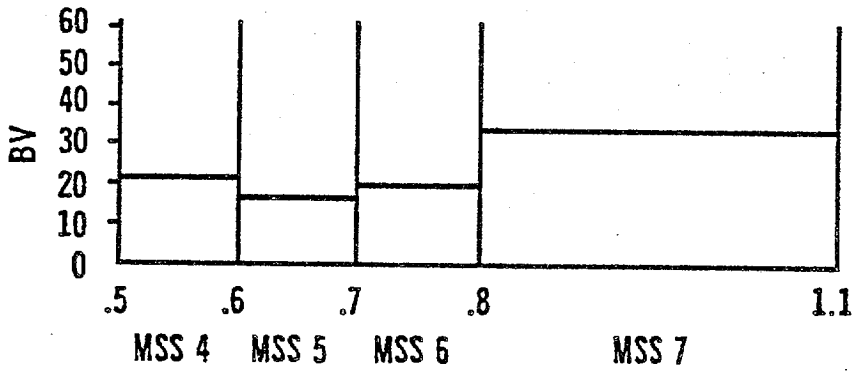

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Figure 36. MSS spectral record of landscape brightness in four wavelength bands, for an area covered by the MSS IFOV that is covered with equal amounts of red sandstone and green vegetation.

of integration of spectral brightness from different cover types and the effects of the atmosphere on spectral brightness, make direct comparisons between ground-based measurements of spectral response from individual cover types and measurements of spectral brightness by the MSS difficult at best. Corrections for atmospheric scattering are routinely applied to Landsat data, but corrections for atmospheric absorption are difficult. (see Taranik, 1977).

TAPE RECORDING OF LANDSAT DATA ONBOARD SATELLITE

Two wide band video recorders, each having a 30 minute recording capacity at 15 megabits of digital data per second, are part of the payload of Landsats 1 and 2. Data are recorded on 2-inch wide tape by four recording heads which are mounted on a rotating wheel that is aligned at right angles to the direction of movement of the tape. The tape recorders may be turned on by direct ground command, or they can be programmed to record data when out of range of ground telemetry. Both recorders are inoperable on Landsat 1 and only one recorder is used in a limited mode on Landsat 2 (Figure 37).

	LANDSAT 1	LANDSAT 2	LANDSAT C	LANDSAT D
MULTISPECTRAL SCANNER	REAL TIME (BAND 4 OUT) (BANDS 5, 6, 7, OK)	REAL TIME AND TAPE RECORDING (BANDS 4,5,6,7,OK)	SCHEDULED LAUNCH: SPRING 1978 BAND 8 THERMAL CHANNEL PLANNED	SCHEDULED LAUNCH: 1981 BANDS 4,5,6,7,8
RETURN BEAM VIDICON	NON-FUNCTIONAL	FUNCTIONAL BUT LIMITED OPERATIONS	HIGHER RESOLUTION PANCHROMATIC RBV PLANNED	THEMATIC MAPPER SUBSTITUTED (6 BANDS)
TAPE RECORDERS				
1	NON-FUNCTIONAL	PARTLY FUNCTIONAL		
2	NON-FUNCTIONAL	OPERATIONAL		

E-6207-35

Figure 37. Landsat data collection status.

LANDSAT 1 and 2 DATA HANDLING

After multispectral data are collected by the MSS they are either relayed in real time to a ground station or are recorded for playback in the future. Landsat MSS data are transmitted to the Earth at 15MBPS using a S-band frequency of 2265.5 MHz. NASA maintains three data reception facilities in the United States for Landsat data; Goldstone in the Mohave Desert of California, Anchorage, Alaska and Goddard Space Flight Center in Greenbelt, Maryland (Figure 38). There are foreign receiving sites in Canada (2),

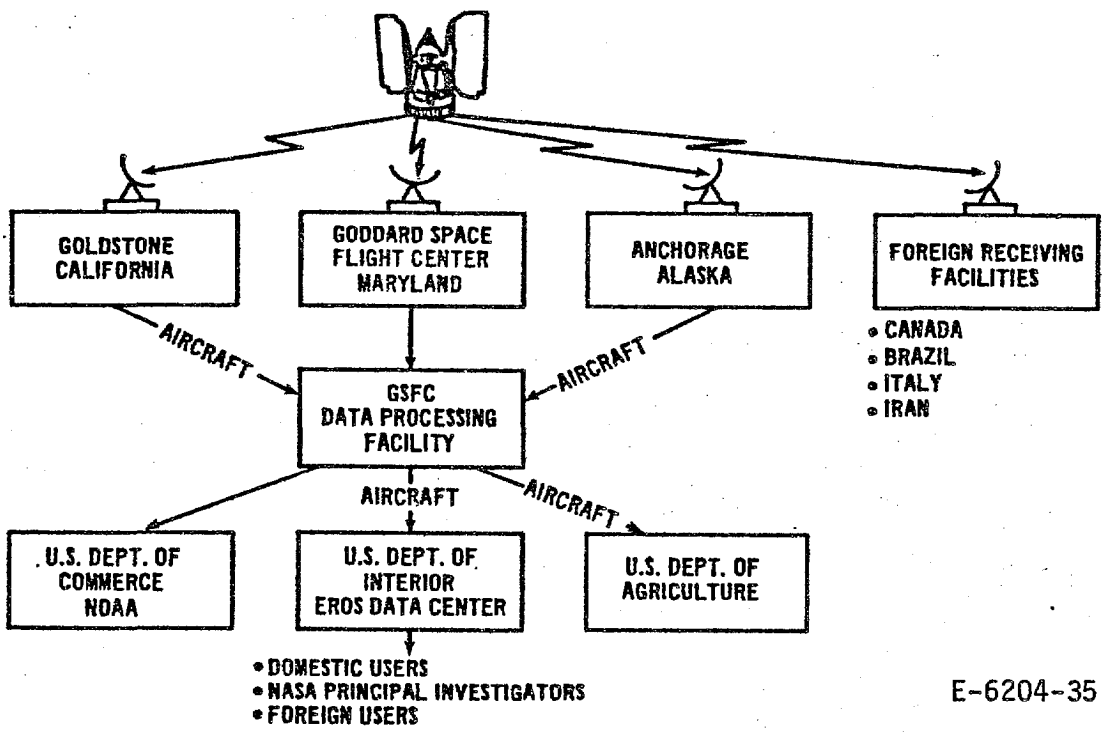

Figure 38. Landsat 1 and 2 data flow.

Brazil, Italy, and Iran (Pakistan until Iran is operational). Negotiations are underway for Asian, South American, and African stations as well (Figure 39).

	LANDSAT 1	LANDSAT 2	LANDSAT C	LANDSAT D
U.S.A. (3)	REAL TIME, USING CLOUD COVER	REAL TIME	LAUNCH 1978	LAUNCH 1981
CANADA (2)	REAL TIME	REAL TIME, USING CLOUD COVER		
BRAZIL	REAL TIME	REAL TIME,SPECIAL REQUEST ONLY		
ITALY	REAL TIME	REAL TIME,SPECIAL REQUEST		
IRAN (PAKISTAN)	REAL TIME	REAL TIME,SPECIAL REQUEST		
REMAINDER OF EARTH	NONE	TAPE RECORDER PER SPECIAL REQUIREMENTS		

OTHER PLANNED RECEIVING STATIONS:

CHILE (AGREEMENT SIGNED)
ARGENTINA (NEGOTIATION)
AUSTRALIA (DISCUSSED)
JAPAN (DISCUSSED)
USSR (DISCUSSED)

E-6208-35

Figure 39. Landsat System mode of operations.

Receiving site equipment arranges multiplexed data into individual data channels, one channel for each detector on the MSS. A preamble line start code and line length code are added to each channel and the data are recorded in parallel lines on video type. The wide band video recordings produced by the receiving stations at remote sites in the United States are shipped by air to GSFC (Figure 38). Foreign stations which receive Landsat data, process their data to imagery and market the data to users in their area.

The operations control center at GSFC produces an image annotation tape which has the mission parameters necessary for annotation and correction of the video tape data from the receiving stations. The NASA Image Processing Facility at GSFC uses the station video tape and the

and the annotation tape to produce master 70mm images from all data collected by the MSS (Figure 40). Computer Compatible Tapes (CCT'S) are only produced on user request.

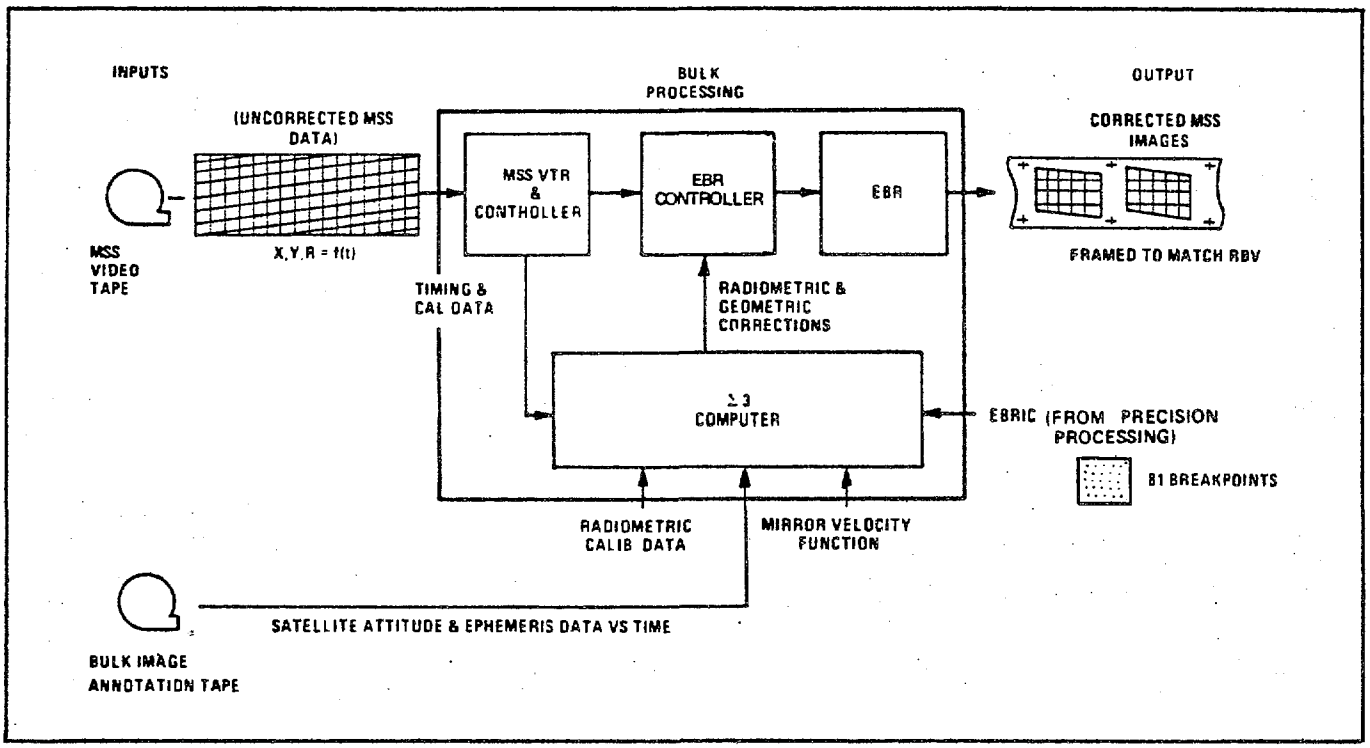

Figure 40. MSS data processing path at the Image Processing Facility at Goddard Space Flight Center. From NASA Landsat Data Users Handbook.

Film recording at GSFC is done on an Electron Beam Recorder (EBR) which produces archival positive images on 70mm wide film (Figure 41). The Electron Beam Recorder functions much like a cathode ray type in an oscilliscope. The intensity of a beam of electrons is modulated as the beam is focussed and aligned by deflection coils onto film. Film recording is done so film transmission on a positive image is linear with sensor brightness value (digital count). The second generation negative (N-2) sent to U. S. Government distribution centers has a density range of 0.4D to 2.4D and a gamma of 1.

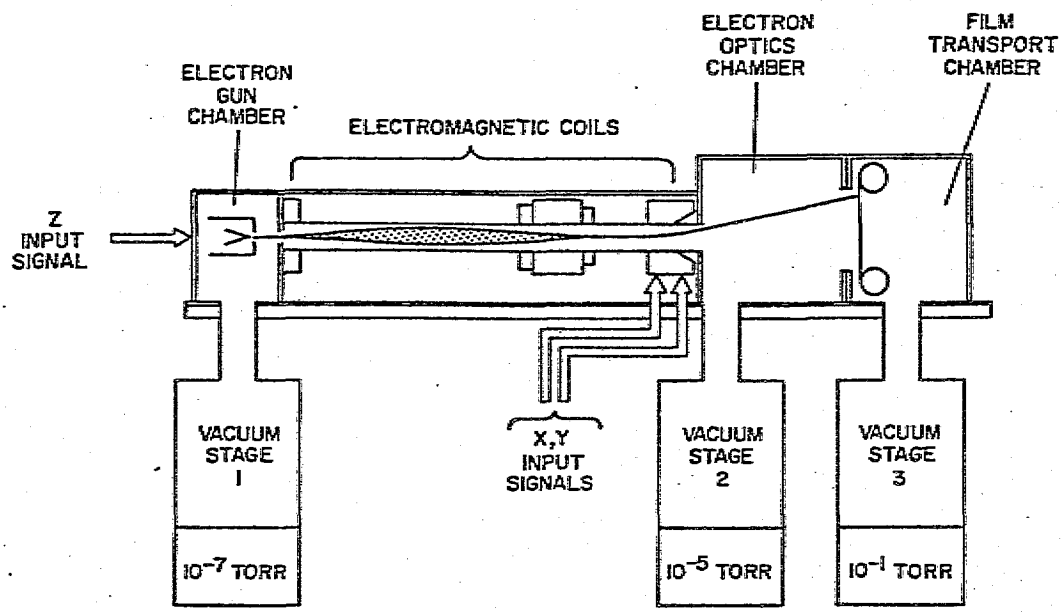

Figure 41. Schematic diagram of the Electron Beam Recorder used to produce Landsat imagery. From Image Graphics, Inc. Brochure.

The EROS Data Center prints the N-2's to third generation, 70mm positives (P-3's), with a density range which is more easily used in the photographic laboratory. The 70mm P-3's are enlarged to 241mm size and are printed as fourth generation negatives (N-4's). This enlargment step optically degrades image resolution to some degree. The 1:1,000,000 scale N-4's are printed to fifth generation positives (P-5's). Band 4, band 5, and band 7 fifth generation positives are pin-registered with color transparency material in the photographic laboratory. Band 4 is exposed on the transparency using blue light, band 5 with green light, and band 7 with red light. The resulting product is a sixth generation color master transparency (CP-6) which is used to produce all other color products. For a complete discusssion of photographic techniques used in producing EDC standard products see Lucas, Taranik, and Billingsley, 1977.

Landsat computer compatible tapes (CCT's) are produced at GSFC from wide band video recordings and annotation tape data. A high density digital tape (HDDT) is produced from the video data. The HDDT contains uncalibrated data, line length code values for each scan line, and radiometric calibration wedge samples (Thomas, 1975, p. D-1). The data are reformatted on the HDDT so bands 4, 5, and 6 have counts from zero to 127 while band 7 remains at zero to 63 (Figure 42).

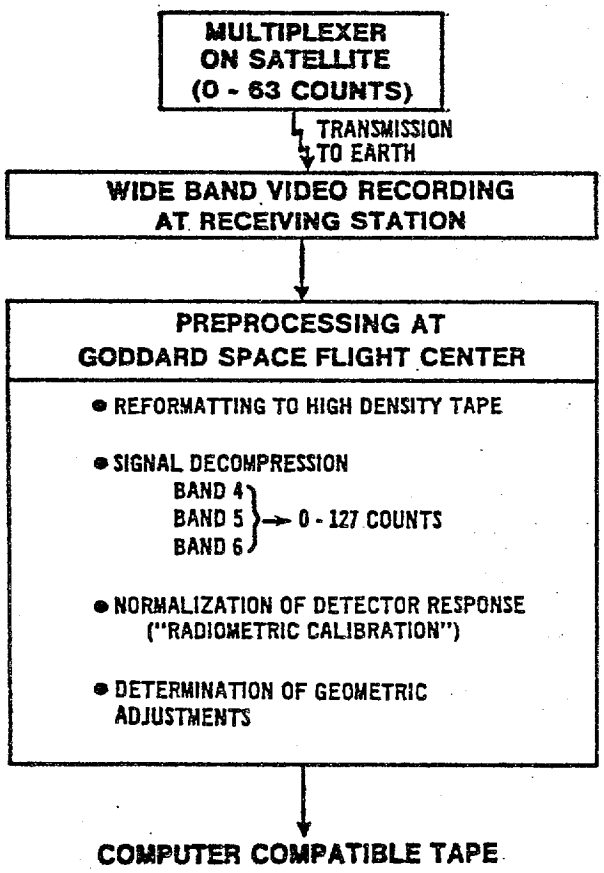

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Figure 42. Data processing path for Landsat 1 and 2 computer tapes.

Normalization for detector response is performed, but it is seldom perfect and residual detector striping remains. See discussion of corrections for striping in Landsat data in Taranik, 1977.

CHARACTERISTICS OF LANDSAT 1 AND 2 DATA

LANDSAT IMAGERY

Coverage of a typical Landsat image is shown in Figure 43. The

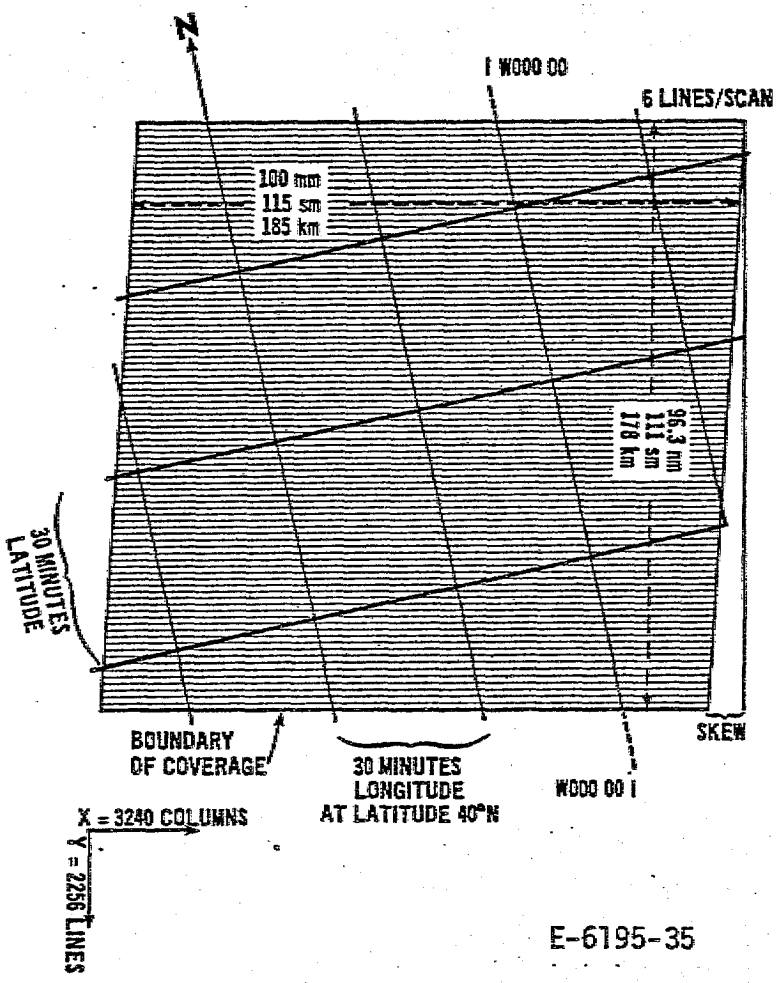

Figure 43. Landsat image coverage. Latitude and longitude lines constructed for an area in Colorado.

image deviates from a rectangle by the distance the Earth rotated under the satellite (skew) during the 25 seconds the data were acquired from the top of the scene to the bottom. Lines of latitude and longitude are at an angle with the sides of the image because of the 99^{0} inclination of the Landsat orbit. The geographic lines are

constructed from the bars at the beginning or the end of numbers designating latitude and longitudes (Figure 43). The annotation of Landsat 1 and 2 imagery acquired prior to February 1977 is shown in Figure 44.

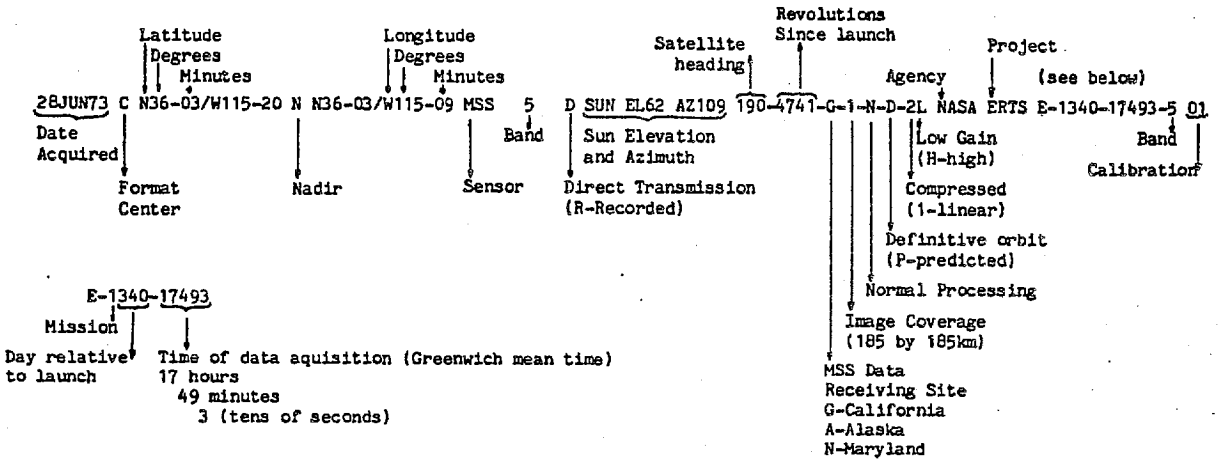

Figure 44. Annotation of Landsat 1 and 2 imagery.

Table 3 shows the relationships of coverage by a single Landsat scene to coverage by standard 9 by 9-inch imagery acquired with a 6-inch focal length, overlap of 60%, and sidelap of 30%.

TABLE 3

- COVERAGE OF 1 LANDSAT SCENE

185 KM BY 178 KM = 32,930 SQUARE KILOMETERS
115 MI BY 111 MI = 12,765 SQUARE MILES

- STANDARD AIRCRAFT COVERAGE OF 1 LANDSAT SCENE

PLATFORM	SCALE	NO. PHOTOS
LOW ALTITUDE AIRCRAFT	1 : 15,000	5000
LOW ALTITUDE AIRCRAFT	1 : 30,000	1500
HIGH ALTITUDE AIRCRAFT	1 : 60,000	300
COMMERICAL JET AIRCRAFT	1 : 90,000	150
GOVERNMENT AIRCRAFT	1 : 120,000	85
MILITARY AIRCRAFT	1 : 250,000	30

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Table 3. Comparison of Landsat coverage with aircraft coverage.

LANDSAT COMPUTER COMPATIBLE TAPES

There are 2340 lines of data on a CCT compared to 2256 lines of data on a standard Landsat image (Figure 45). The EROS Data Center furnishes CCT's in one tape, 1600 Bit per inch format or in two-tape 800 BPI format (Figure 45). One CCT file contains an identification

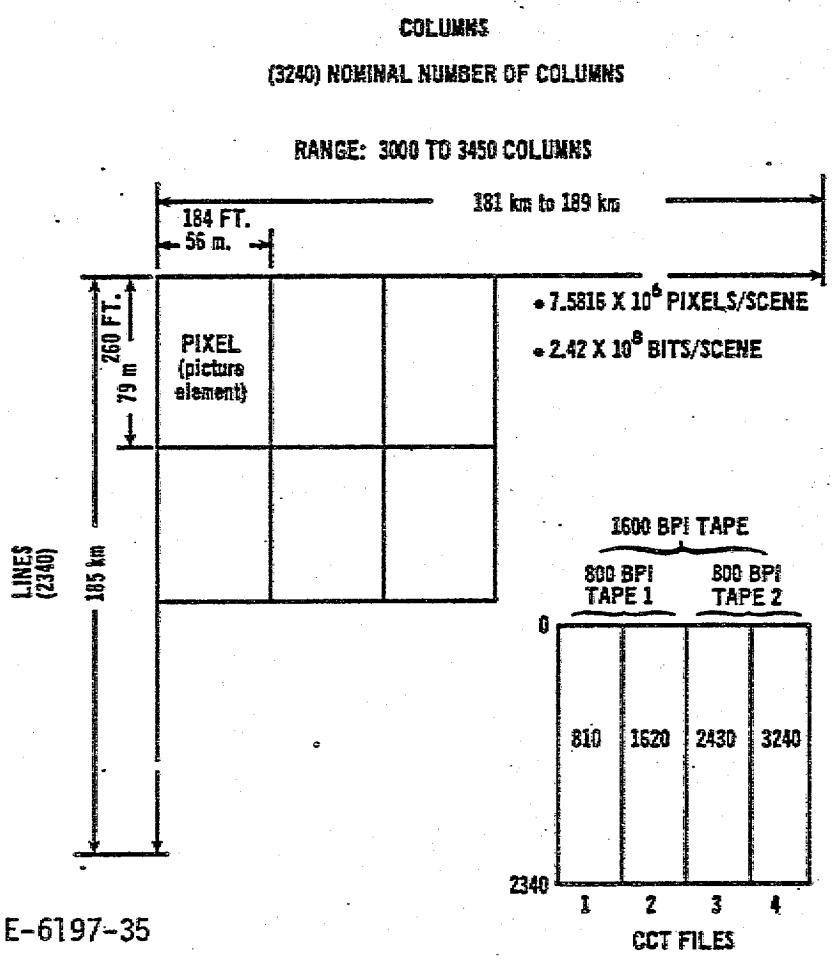

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Figure 45. Landsat CCT format.

record, an annotation record, and 780 line sets of interleaved video data for all Landsat bands. Both film products and CCT's have the same radiometric corrections applied to the data and they are both adjusted for line length. CCT's are not corrected for variations in mirror velocity

earth rotation, or mapping projection (Thomas, 1975, p. 7).

Computer compatible tapes are being used in increasing numbers by geologists in mineral and petroleum exploration. Digital processing and analysis of computer tapes involves three procedures; data preprocessing, image enhancement, and image classification. Data preprocessing involves correction of system introduced errors, corrections for the atmosphere and solar illumination and registration of data. Image enhancement is performed to make spatial patterns dispalyed by tones and color, more apparent on imagery. Image classification is performed to delineate multispectral patterns from image data (Figure 46). Interactive multispectral

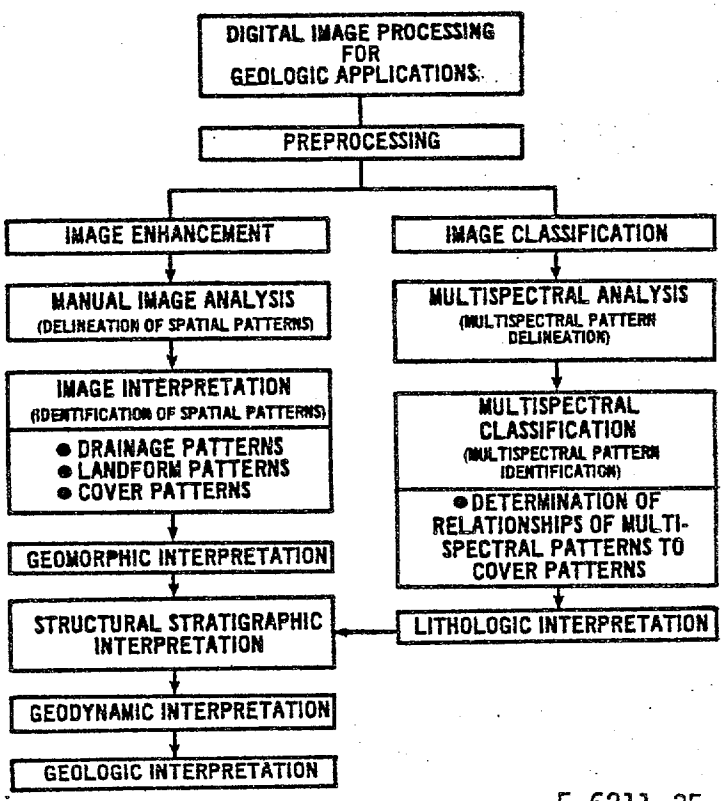


Figure 46. Procedures for digital image processing for geologic applications.

analysis systems allow individual picture elements to be analyzed and displayed using statistical and mathematical processing functions (Taranik, 1977).

The EROS Data Center has been experimenting with the production of digitally enhanced Landsat products (Rohde, Taranik, and Maas, 1977). The enhanced products are produced from digitally preprocessed Landsat CCT' on a laser beam recording system. Data for each wavelength band are recorded on 241 mm wide film over a 1.6 density range. The EROS Data Center Digital Image Enhancement System (EDIES) is an experimental system which will be replaced by the data handling system for Landsat-C. Products for general users are available under the EDIES program at EDC and a complete description of the techniques used in producing the enhanced imagery appears in Rohde, Lo, and Pohl, 1977.

CHARACTERISTICS OF LANDSAT-C OF IMPORTANCE TO GEOLOGISTS

Landsat-C has a scheduled launch in the Spring of 1978. The satellite will carry the same Multispectral Scanner as Landsats 1 and 2, except that an additional channel (band 8) will be utilized to record temperature variations of the Earth's surface. The Return Beam Vidicon sensor will be utilized, but in a modified form to allow increased spatial resolution at the expense of spectral resolution and ground coverage.

THE MULTISPECTRAL SCANNER ON LANDSAT-C

The MSS on Landsat-C will have an identical configuration as the instrument utilized on Landsats 1 and 2 for the channels which detect solar radiation reflected from the Earth's surface (Bands 4, 5, 6, and 7). A thermal channel has been added on Landsat-C and it detects thermal

radiation which is emitted from the Earth's surface at 10.2 to 12.6 micrometer wavelengths. Most of the thermal radiation detected by this channel will have come from the sun and was absorbed by the Earth's surface in the visible and near visible portions of the electromagnetic spectrum (Figure 47). However, local "geothermal" anomalies, which are related to transfer to heat from the Earth's interior to the surface, may be detectable on band 8 if they are of a large enough size and high enough temperature.

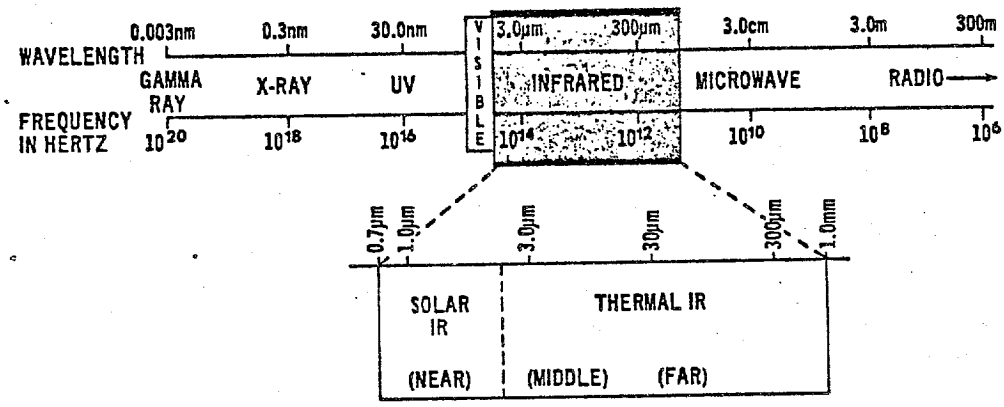


Figure 47. Thermal portion of the electromagnetic spectrum.

The two thermal infrared detectors used for band 8 cover the same area on the ground as the six detectors used for each wavelength band in bands 4, 5, 6, and 7. The size of the band 8 fiber optic bundles at the focal plane of the MSS optics is three times the size of the fiber optic bundles for the other MSS bands (Figure 48). This gives band 8 an instantaneous field of view on the ground of 238 m by 238 m. The voltage sampling interval for the two thermal detectors results in a band 8 picture element having dimensions 167 m by 238 m (Figure 49).

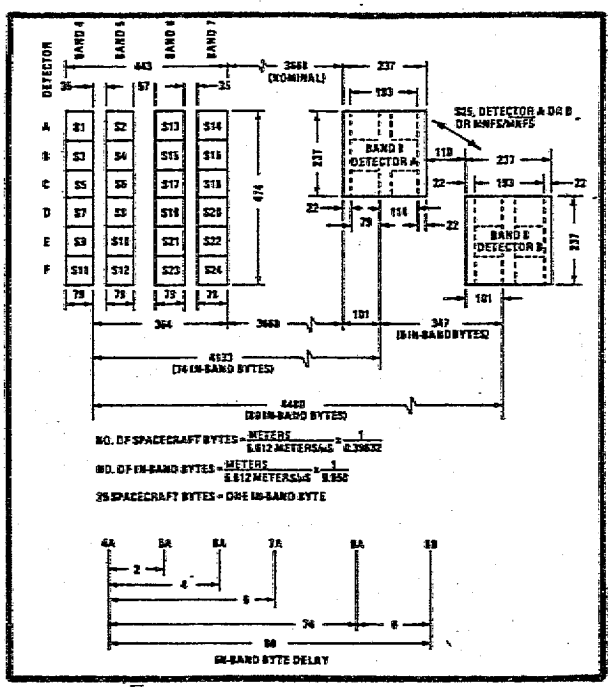
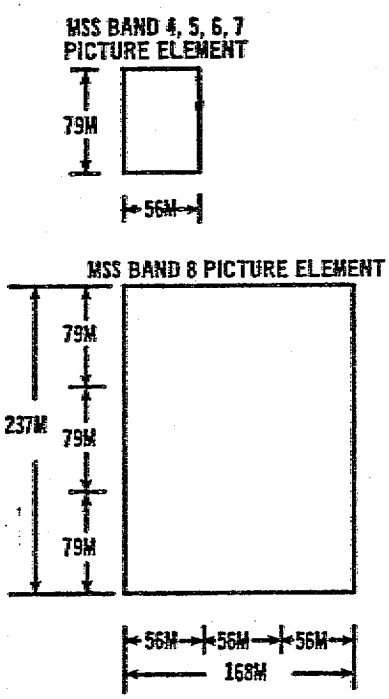


Figure 48. Configuration of the fiber optic bundles in the focal plane of the MSS for Landsat-C. NASA Landsat Data Users Handbook



IFOV	PICTURE ELEMENT	SENSOR BAND
6,240 SQ. M 67,600 SQ. FT.	4,420 SQ. M 47,840 SQ. FT.	MSS 4, 5, 6, 7
56,170 SQ. M 664,600 SQ. FT.	39,820 SQ. M 428,580 SQ. FT.	MSS 8

1 FOOTBALL FIELD ≈ BAND 4 - 7 PIXEL ≈ 1.1 ACRE

9 FOOTBALL FIELDS ≈ BAND 8 PIXEL ≈ 10 ACRES

E-6201-35

Figure 49. The Landsat-C band 8 picture element compared to picture elements for bands 4, 5, 6, and 7.

The band 8 detector response is specified to give a 1.52°K Noise Equivalent Temperature Difference at 300°K. This specification means that an area of the size of six football fields must have a temperature difference of 1.0° C over background to be detected by band 8. The gain of band 8 can be linearly adjusted by ground command into 8 different levels.

THE RETURN BEAM VIDICON

The Return Beam Vidicon system utilized on Landsats 1 and 2 is a three television camera system which records landscape brightness in three wavelength bands (Table 2). The operation of each TV camera is similar to the operation of the camera system on Landsat-C. When the camera shutter opens, radiation is focussed on a phosphor screen. The screen is scanned by an electron beam to detect minute voltages which are, in turn, amplified by a five stage multiplier (Figure 50). The three cameras on Landsats 1 and 2

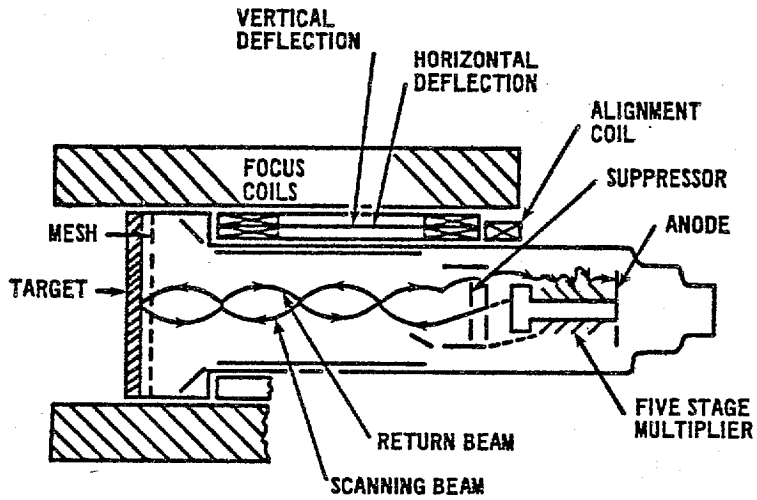


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Figure 50. Schematic of the RBV system vidicon tube.

imaged a 185 Km by 185 Km square area every 25 seconds when the sensor was operable (Figure 51). For Landsat-C a decision was made to increase RBV resolution from 80 m to 40 m and to use one broad wavelength band from 0.505 micrometers to 0.750 micrometers. The resolution of the RBV

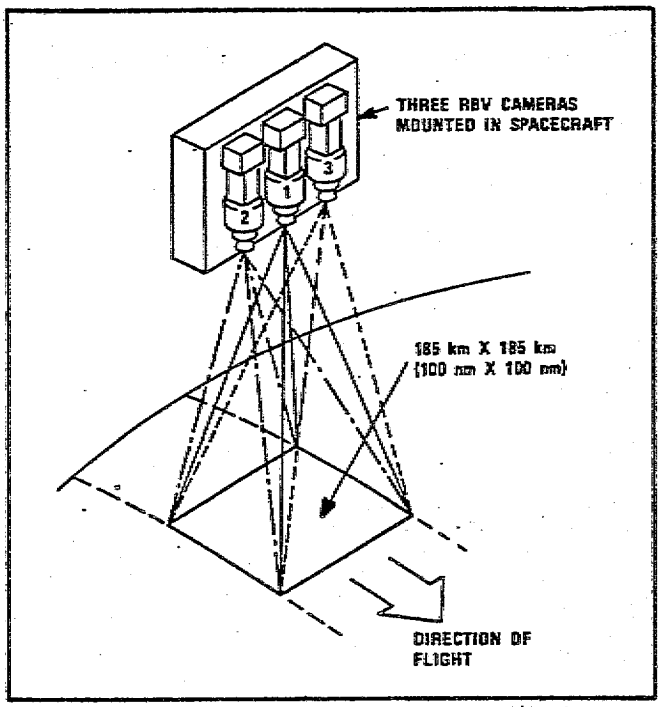

Figure 51. Three camera RBV system on Landsats 1 and 2. From NASA Landsat Data Users Handbook.

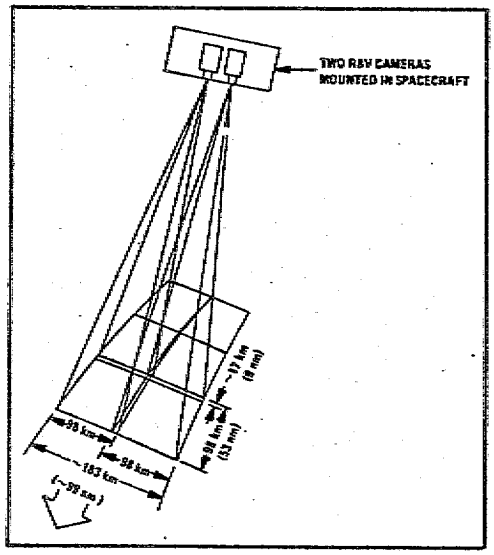

Figure 52. Two camera RBV system planned for Landsat-C. From NASA Landsat Handbook.

was improved by doubling the focal length of the optics. This reduced areal coverage to one quarter of the area covered by a single RBV camera used on Landsats 1 and 2. Two cameras are employed on Landsat-C and they have twice the cycling rate to obtain the same areal coverage as the RBV system on Landsats 1 and 2 (Figure 52). Landsat-C coverage is shown on Figure 53.

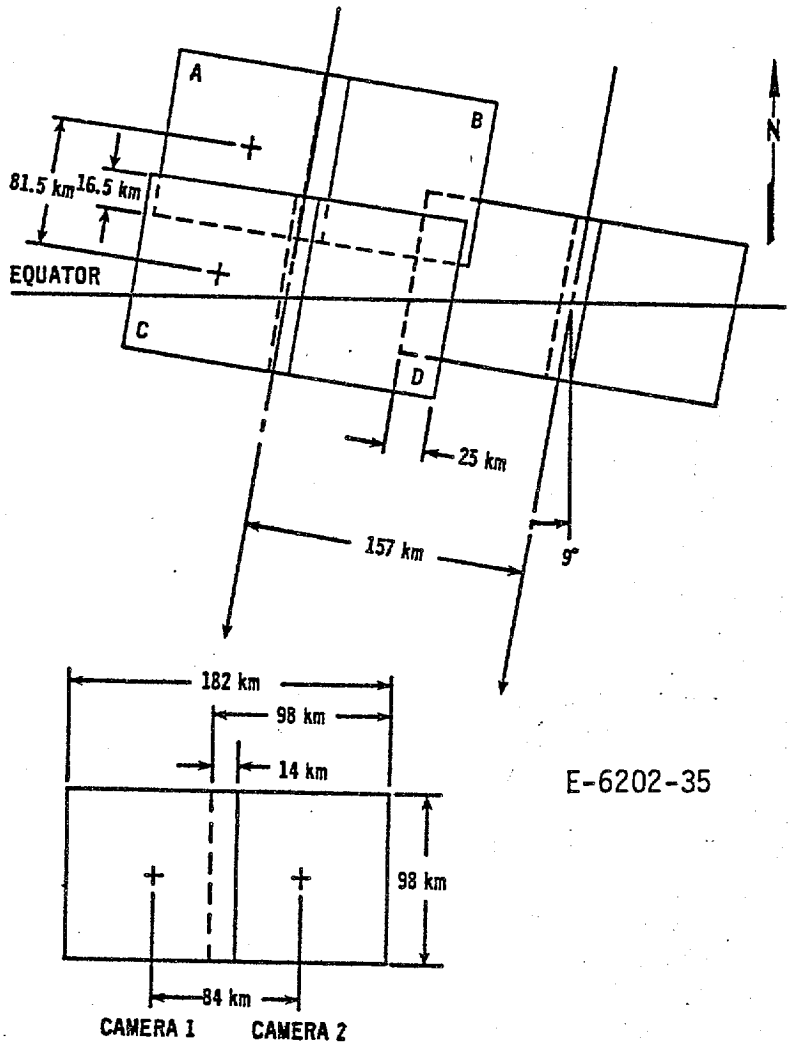

Figure 53. Coverage of the Landsat-C RBV system.

The increased spatial resolution of the RBV sensor on the Landsat-C mission may allow drainage and landform patterns to be more easily analyzed. Because RBV imagery will be similar to panchromatic photography, MSS data will have to be analyzed along with RBV data to evaluate cover types.

LANDSAT-C DATA HANDLING PLAN

A proposed data handling plan for Landsat-C data is shown in Figure 54.

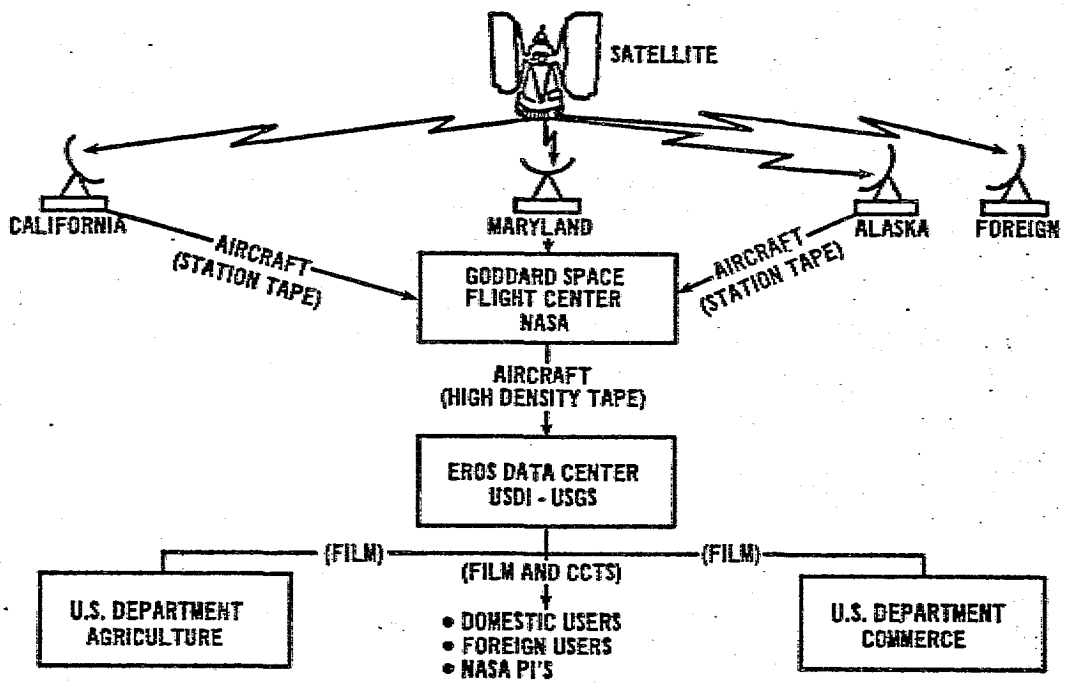

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Figure 54. Proposed data handling plan for Landsat-C data.

Film products and CCT's for all Landsat data produced in the Landsat-C time frame will be produced at EDC for the general user community. EDC will produce master film products using the EROS Data Center Digital Image Processing System (EDIPS). This system will produce master images at 241 mm size using a high resolution Laser Beam Recording System. Digital preprocessing will be utilized to correct for imperfections in the original data and image enhancement will be used to record the data on film in a manner that facillitates efficient reproduction. When the EDIPS system becomes operational in 1978, the EDIES experimental system will be discontinued.

LANDSAT-D

The mission parameters for the Landsat-D satellite to be launched in 1981 have not been completely defined as of October 1977. Current plans define the prime sensor system as a six or possibly seven channel multi-spectral scanner called the Thematic Mapper (TM). Most of the spectral bands on the TM were selected for agricultural applications. The possible seven channels for the TM are the following:

Channel 1	0.45 - 0.52 m	visible blue-green
Channel 2	0.52 - 0.60 m	visible green
Channel 3	0.63 - 0.69 m	visible red
Channel 4	0.76 - 0.90 m	invisible solar infrared
Channel 5	1.55 - 1.75 m	invisible solar infrared
(Channel 6)	(close to 2.2 M)	(invisible solar infrared) 1
Channel 7	10.4 - 12.5 m	invisible thermal infrared

1 Proposed by geologists for research in rock spectral reflectance.

The Thematic Mapper will have a ground IFOV of 30 m for channels 1 to 6, and an IFOV of 120 m for channel 7 if the satellite is flown at a recommended lower altitude of 705 Km. The TM will measure landscape brightness in 256 levels instead of the 64 levels used by the MSS of Landsats 1, 2, and C.

Other recommendations include, flying the Landsat-D satellite at 918 Km and including the MSS used on Landsat-C as the prime sensor. The TM would then be used in an experimental mode over selected research areas because the very high data collection rate of the system would inundate most data collection and processing facilities. The increase in orbital altitude will increase the ground IFOV of the TM from 30 to 40 meters.

A tentative data handling plan for Landsat data distributed to the EROS Data Center is shown in Figure 55. Domestic communication satellites will be probably used in the 1980's to relay data from remote antennas to Goddard Space Flight Center and from GSFC to the EROS Data Center. This data relay system should make data available to users in a matter of a few days.

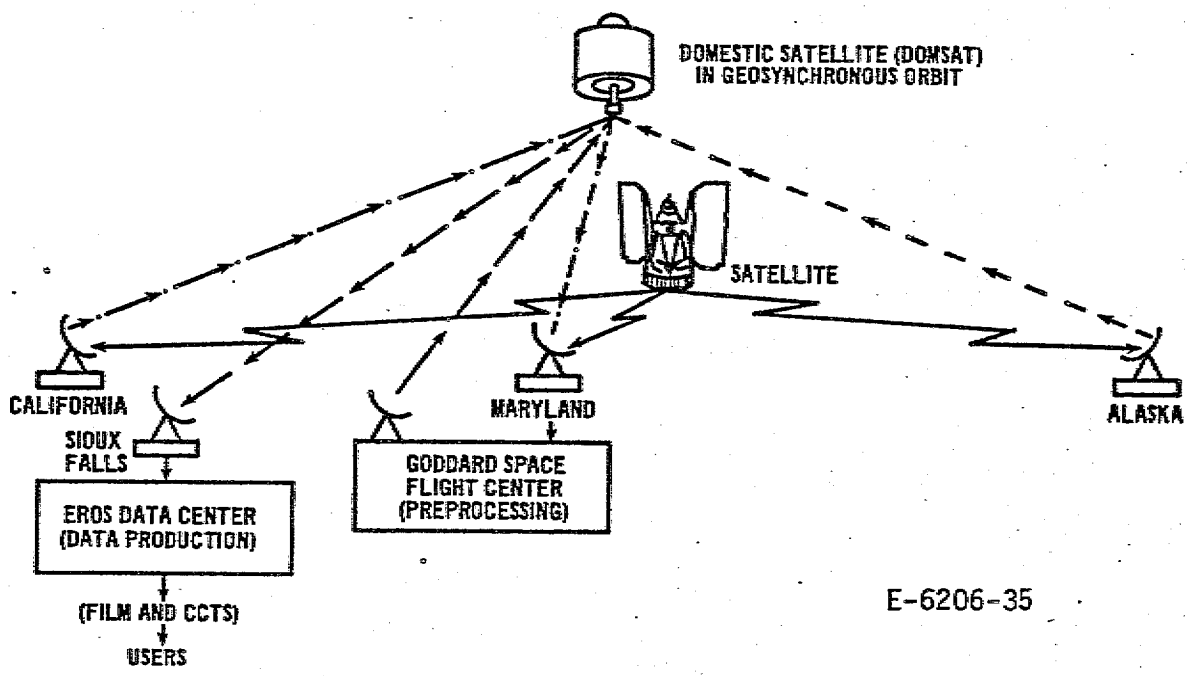

Figure 55. Possible data handling plan for data produced in the Landsat-D time frame

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Bryan Bailey

REFERENCE MATERIALS ON PRINCIPLES OF COMPUTER PROCESSING OF LANDSAT DATA FOR MINERAL AND PETROLEUM EXPLORATION

EROS DATA CENTER

U. S. Geological Survey

Sioux Falls, South Dakota

These reference materials were prepared for training courses in geological remote sensing at the EROS Data Center. The materials are a supplement to lectures illustrated with 35mm slides. Slides are available from the EROS Data Center Public Affairs Office if the illustration has a number located on it which is of the format E-00000-35. This PAO number should be referenced when slides are ordered.

James V. Taranik
U. S. Geological Survey

October 1977

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INTRODUCTION

When Landsat 1 was launched in 1972 the U. S. Geological Survey expanded its research in digital image processing to include Landsat data. Research in computer processing of Landsat data for geological applications was conducted in the Survey's Geologic Division in two organizations--The Center for Astrogeology in Flagstaff, Arizona and the Branch of Petrophysics and Remote Sensing in Denver, Colorado. Much of this research was conducted jointly with the Image Processing Laboratory in the Jet Propulsion Laboratory of the California Institute of Technology in Pasadena, California. These training materials are developed largely from the publications of these three organizations. Users of this material should consult the publications listed in the bibliography.

IMAGE PROCESSING FOR GEOLOGIC APPLICATIONS

The main objectives of computer processing of Landsat data are to improve display of image data to the analyst or to facilitate evaluation of the multispectral characteristics of the data. Digital processing techniques are employed with Landsat data because:

1. The original data are in digital form
2. System related errors can be rectified
3. Corrections for sun illumination and atmospheric effects can be applied
4. Individual picture elements can be analyzed and displayed
5. Mathematical processing functions can be utilized
6. Statistical analysis techniques can be employed
7. Large amounts of data may be processed and analyzed in short periods of time

For most applications digital image processing involves three procedures; data preprocessing, image enhancement, and image classification. Data preprocessing involves the correction of system introduced errors, corrections for atmospheric and solar illumination variations, and it involves registration of data. Image enhancement is performed to make spatial patterns displayed by tones and color, more apparent on imagery. Image classification is performed to delineate multispectral patterns from image data (figure 1).

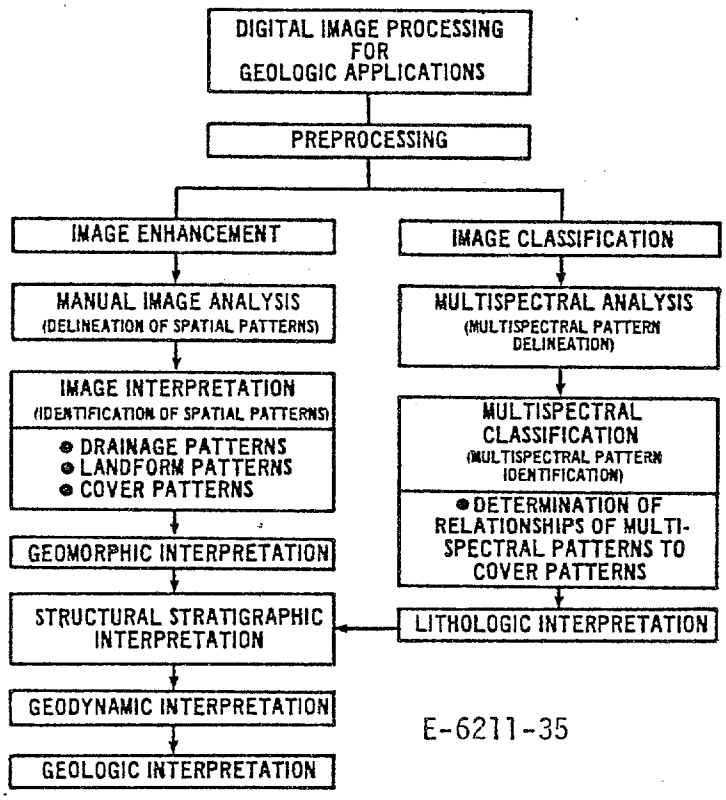

Figure 1. Procedures for digital image processing for geologic applications

Geologic interpretations are developed from enhanced and classified image data through the use of a stepwise procedure which must involve an interpreter with training in geology. Manual image analysis involves delineation of spatial patterns on imagery. Image interpretation involves identification of spatial patterns on imagery as landform, drainage, and cover patterns. An image analyst with training in geology must analyze the landscape patterns on imagery to interpret geomorphology. Geomorphologic relationships are analyzed to develop structural and stratigraphic interpretations. Geodynamic interpretations are developed through the analysis of structural and stratigraphic relationships. Geologic interpretations are developed through analysis of geodynamics, structure, stratigraphy, and geomorphology. Multispectral pattern analysis involves machine assisted multispectral pattern delineation. Multispectral classification of delineated multispectral patterns must be done by an analyst who determines the relationships of multispectral patterns to landscape cover patterns. If there is a strong relatipnship between the economic deposits being explored for and the cover patterns (e.g. between base metals and surface alteration zones) then an exploration plan may be developed on the basis on an image classification. Usually multispectral classifications must be incorporated with structural and stratigraphic interpretations, and the resource exploration plan must be based on a geologic interpretation which is developed from both spatial and multispectral patterns in image data (Figure 1).

HISTOGRAMS OF BRIGHTNESS VALUES

Image enhancements and image classifications often involve the evaluation of histograms of the data to be processed. Image enhancements involve adjustments of brightness values for individual picture elements. Image classification involves determination of the brightness values of picture elements for a particular cover type. Histograms are commonly used to display the range and frequency of occurrence of brightness values. A spatial array of picture elements in part of one Landsat band is shown in figure 2. A histogram of the pixel values in the spatial array is shown in figure 3.

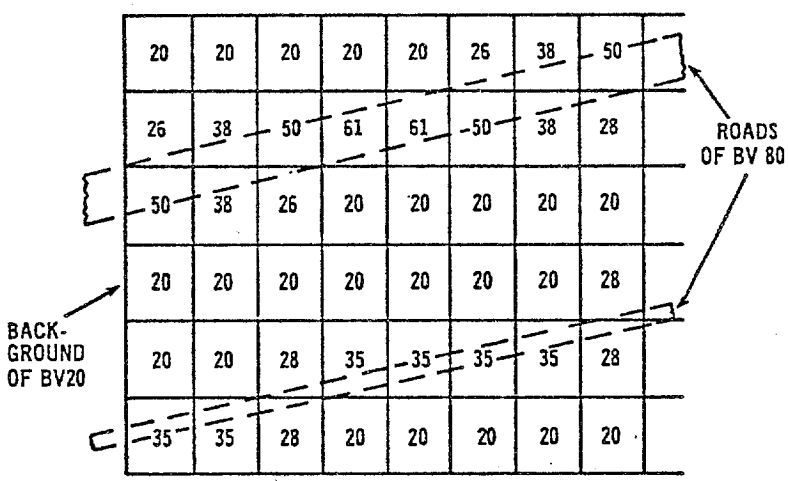

Figure 2. Spatial array of pixels

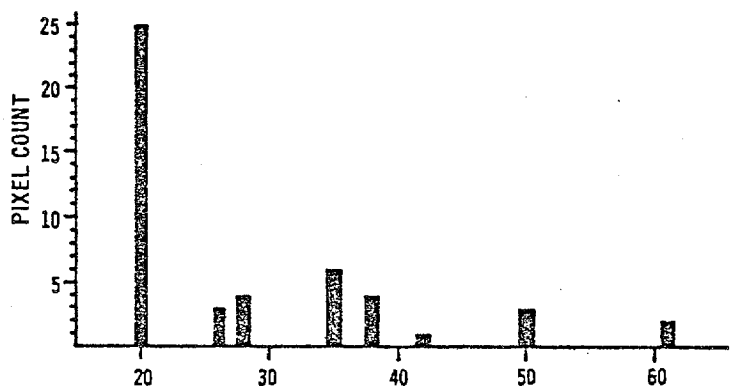

Figure 3. Histogram of brightness values of pixels in spatial array

An image enhancement technique might shift brightness values so only brightness values associated with roads are shifted to the right on the histogram. Thus there would be a larger brightness differential between roads and the background against which roads were imaged. An image classification technique might group brightness values associated with the background from brightness values associated with roads in four spectral bands.

Because one Landsat computer compatible tape (CCT) contains 7, 581, 600 picture elements (pixels) it is not practical to display all the counts of picture element brightness values graphically in a histogram. Histogram displays are usually "normalized" so that the maximum count of picture elements of one brightness value is displayed as 100% on the ordinate axis. All other counts of picture elements of a particular value that are less than the maximum count are adjusted relative to the maximum count so that they are percentages of the maximum count (Figure 4).

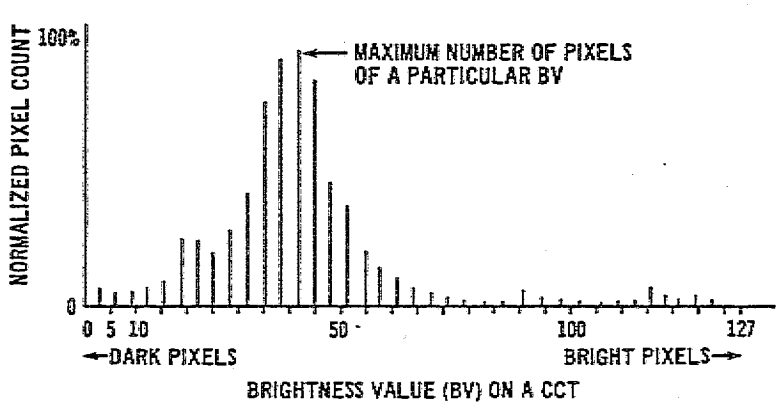

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Figure 4. Histogram display of occurrence of brightness values in one Landsat band

The abscissa usually has values of 0 to 127 for bands 4,5, and 6, and values of 0 to 63 for band 7 if the data are read directly from a CCT. Most computer processing is done in 8-bit mode, and in this case, the histogram abscissas have values of 0 to 255.

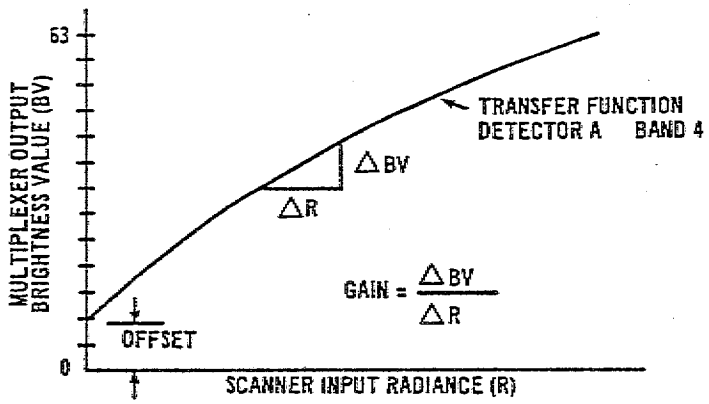
PREPROCESSING OF LANDSAT 1 AND 2 DATA

RADIOMETRIC RECTIFICATION

Landsat 1 and 2 data are converted from wide-band video tape recordings at Goddard Space Flight Center (GSFC) in Greenbelt, Maryland. Some preprocessing is done at GSFC to correct for variations in the response of the 24 MSS detectors. Because illumination conditions and landscape characteristics vary considerably and detector response changes with time the radiometric corrections for detector response are seldom perfect and usually striping is produced on Landsat film products. Bad data lines and line segments, and individual pixel data dropouts are also common radiometric errors on Landsat products.

Corrections for Striping in Landsat Data

Striping in Landsat data results from differences in the response characteristics of the 24 MSS detectors. Specifically the detectors have different gains and offsets (Figure 5). There are several methods for minimizing this problem including filtering, histogram normalization, and histogram normalization with local average adjustment. Histogram normalization with local average adjustment is the process employed with the EROS Data Center Digital Image Enhancement System (EDIES) and the following description of the process utilized is borrowed from Rohde, Lo, and Pohl, 1977. "Effects of striping in each MSS band are minimized by a two-pass operation. In the first pass, data from



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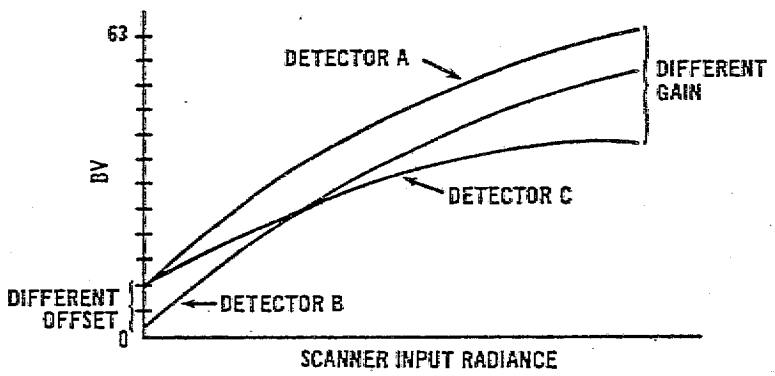
DEFINITION OF GAIN AND OFFSET



DIFFERENT GAINS AND OFFSETS
FOR 3 BAND 4 DETECTORS IMAGING
THE SAME LANDSCAPE CONDITIONS

Figure 5. Causes of striping in Landsat data

each detector are normalized with the relationship:

$$DN_O = DN_I \times \frac{S_A}{S_I} + \left(M_A - M_I \times \frac{S_A}{S_I}\right) \qquad (1)$$

where:

DN_O = Brightness value of pixel in output image

DN_I = Brightness value of pixel in input image

S_A = Standard deviation of entire scene

S_I = Standard deviation of individual detector

M_A = Mean brightness value of entire scene

M_I = Mean brightness value of indivudual detector

The correction, with this approach, is based on statistics calculated from the entire scene. However, in some subregions of a scene, the

"local" statistics are quite different from statistics calculated from an entire scene. When this occurs, the one-pass algorithm may not be effective and residual striping may be observed. The second pass performs a local average adjustment to remove residual striping from the first pass. In the second pass, data are processed in groups of six lines. The first line is chosen as a good data line and each succeeding line is processed to be similar to the preceding line. The first line remains unchanged as it is the reference line. A local average along line I ($LOCAV_{I-1}$) of plus or minus 75 pixels around the pixel being processed in a line is compared to the corresponding local average in the preceding line I -1 ($LOCAV_{I-1}$). Before pixels are used to compute the local average, the pixels are subjected to an edge test. If the absolute value of the differerence between brightness values of pixels in adjacent scan lines is greater than a specified threshold value, it is assumed a real edge exists in the data, and the pixels are not used to calculate the respective local averages. Once the local averages have been computed, the difference between the local average around a pixel in a given line and the local average around a pixel in the preceding line is computed. If the absolute value of this difference is less than a specified threshold value, the pixel brightness value is modified by the difference and is computed from the formula:

$$DN_0 = DN_I - D \qquad (2)$$

where:

DN_0 = Digital number or brightness value in output image

DN_I = Digital number of brightness value in

$D = LOCAV_I - LOCAV_{I-1}$

This second operation, although time consuming, does appear to remove residual striping often found if only the first operation were used."

Corrections for Bad Data Lines in Landsat Data

Two methods are commonly employed in replacing bad data lines in Landsat data. One method uses an interpolation procedure to replace the bad data line with values determined by interpolating between the brightness values in the preceding line and the line following the bad data line. In the EDIES system a second technique is employed which replaces the brightness values in the bad data line with values in the preceding line. Bad data lines are identified in EDIES by calculating the standard deviations and mean values of the first six scan lines. By comparing these statistics, a good line is selected as the first reference line. Then a two-by-two pixel edge detector is applied to the reference line and the next scan line. The detector moves horizontally across the scan lines one pixel at a time. The brightness values for the 4 pixels are subjected to a test. When the absolute value of a pixel in the next line and the line above is greater than a threshold value a horizontal edge (bad data point is assumed). When 150 consecutive bad data points are counted the entire scan line is replaced by the brightness values in the entire line above (Rohde, Lo, Pohl, 1977).

GEOMETRIC RECTIFICATION OF LANDSAT DATA

Landsat CCT data also have geometric characteristics which must be corrected if image data are to be correctly displayed to the analyst. Rotation of the Earth under the satellite and movements of the satellite platform introduce geometric distortions in the data.

Correction for Earth Rotation

The "skew" caused by rotation of the Earth under the satellite is a function of latitude and spacecraft heading. Each scene is deskewed by an algorithm that shifts scan lines to the right depending on the latitude of the line. This type of geometric correction insures that landscape features are in relative position with respect to each other throughout the scene.

Line Length Correction

The variable velocity of the MSS mirror scanning mechanism and variations in the altitude of the satellite platform from 880 km to 940 km cause variations in the line length of MSS data. The correct line length, based on a model of orbital and instrument parameters is 3318 pixels. Landsat 1 and 2 imagery is produced with a line length of 3240 pixels at GSFC. Usually the number of pixels along a line in a CCT is close to 3240. Therefore pixels must be inserted at intervals to adjust line lengths to 3318 pixels. This correction is done using a piece-wise linear interpolation method. Each scan line is divided into eight equal segments, and each segment is partitioned into a given number of pixels (n). Ground displacement errors (d) for each segment are computed at GSFC. Each segment is then repartitioned into n + d equal parts. The center coordinates of each equal part is the new pixel location in that segment. The brightness value for each new pixel added to the line is derived by linear interpolation between the brightness values of the pixels before and after the added pixel. This process is repeated for each of eight segments in all scan lines in the scene (Rohde, 1977). Pixel insertion may cause some problems with viewing Landsat data in stereo using the side-lapped portions of Landsat

images, becuase it may destroy the relief-displacement present in the uncorrected data.

CORRECTION FOR SOLAR ILLUMINATION

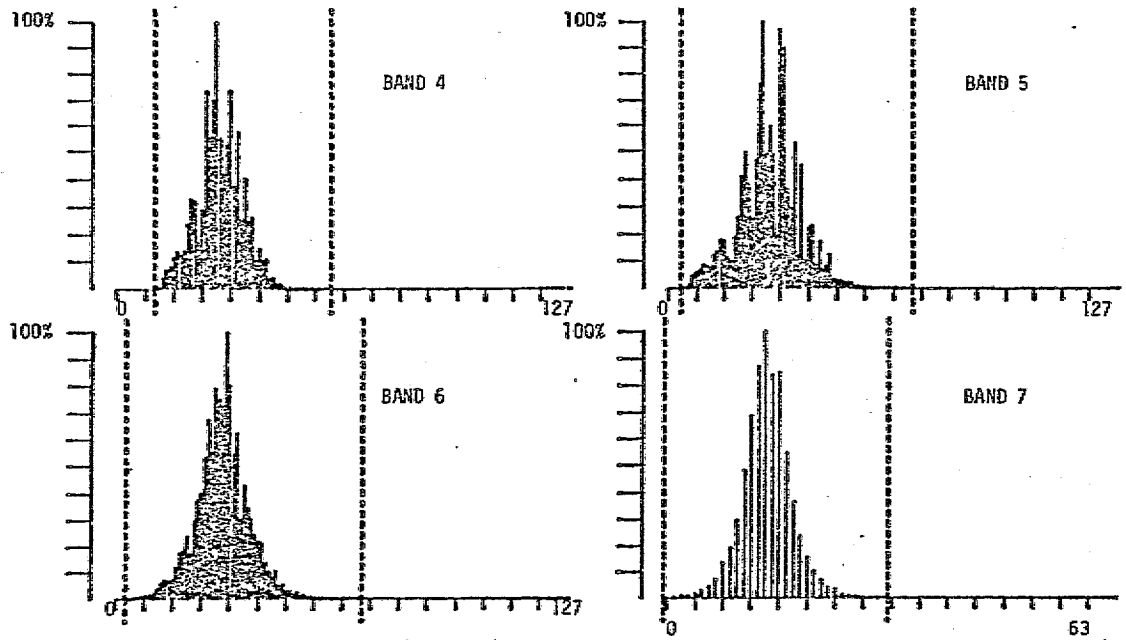
This is a correction applied to adjacent scenes of Landsat data that are to be electronically mosaicked and that were acquired under different illumination conditions. This type of correction is also necessary for comparison of spectral properties of cover types for scenes acquired under different conditions of solar illumination. The sun elevation angle (sun angle) correction involves multiplication of all brightness values in the scene by a constant which is a function of the sun angle. The function assumes a Lambertian surface and is derived by dividing by the cosine of the incidence angle (Chavez, 1975). This correction does not remove the effects of topography which influence the total flux per unit area of radiation received by slopes facing and facing away from the sun (Taranik and Trautwein, 1977). It also does not correct for different azimuths of solar illumination. These latter two types of problems require digitized topographic data and extensive processing time.

CORRECTION FOR ATMOSPHERIC EFFECTS

The atmosphere affects data acquired by the Landsat MSS in two ways. Atmospheric scattering adds a brightness value to the data that is inversely proportional to the fourth power of the wavelength. Short wavelengths of electromagnetic radiation are affected proportionally more than longer wavelengths. Atmospheric absorption subtracts brightness values at the longest wavelengths detected by the MSS (band 7). The

result of these effects is to cause band 7 to often have zero brightness values present, even when there are no objects of zero reflectance in the scene, and to cause bands 6, 5, and 4 to have proportionally increasing brightness values for their darkest pixels. These relationships are shown on Figure 6, which is a reproduction of actual data for a "hazy" scene in Wyoming. The lowest brightness level in band four is 11, the lowest brightness level in band five is 4, the lowest brightness level in band six is 3, and band seven has a brightness value of 0. If the histograms of bands 4, 5, and 6 are shifted so that zero values just appear in their data then the effects of atmospheric scattering will have been minimized (this is often called "haze removal"). The displacement of values is accomplished by subtracting the lowest brightness value in a band from all brightness values in the band (Figure 7). Normally this operation is accomplished during a contrast stretch of the data because contrast enhancement expands data values to the entire brightness value range between zero and 127, or zero and 255 if the data are scaled to 8-bit mode.

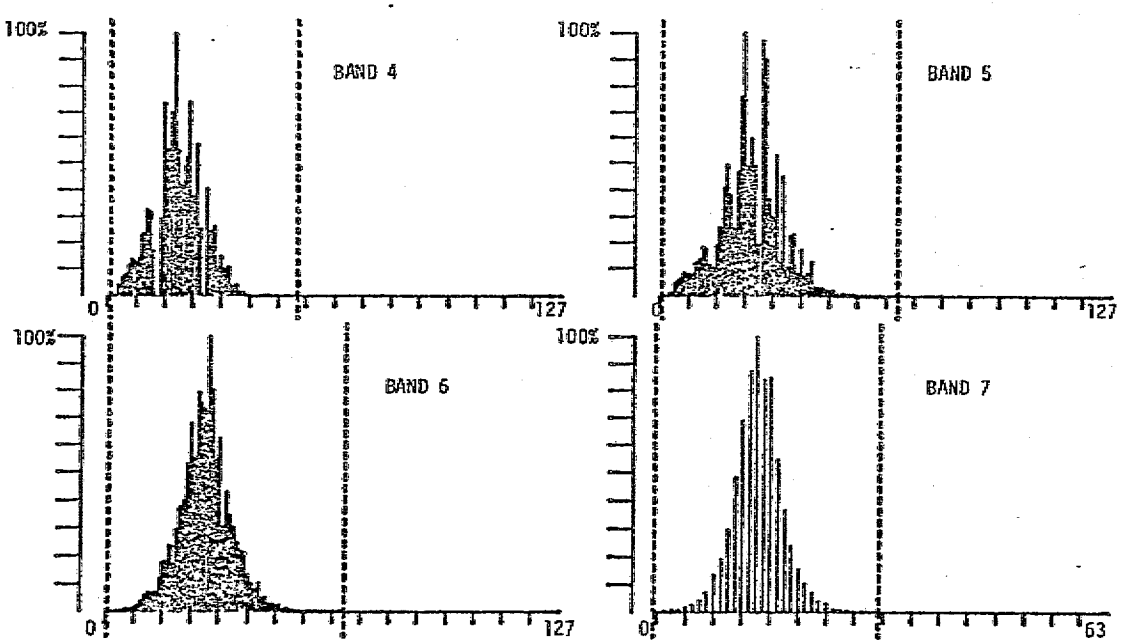
Corrections for atmospheric absorption are difficult because atmospheric absorption is largely a function of water vapor in the atmosphere. The amount of water vapor is highly variable from scene to scene, but it can usually be modeled for one scene if sufficient weather station data is available on total precipitable water on the date and time the satellite data were acquired. Atmospheric scattering and absorption greatly influence the measurement of spectral characteristics of cover conditions. If comparisons are to be made between ground-based spectral measurements and satellite measurements then corrections for atmospheric effects must be applied.



Spectral band	low bound	high bound
Band 4	11	60
Band 5	4	69
Band 6	3	69
Band 7	0	31

POWDER RIVER BASIN SUBSCENE

Figure 6. Data values prior to correction for atmospheric scattering.



Spectral band	low bound	high bound
Band 4	0	59
Band 5	0	65
Band 6	0	66
Band 7	0	31

POWDER RIVER BASIN SUBSCENE

Figure 7. Data values after correction for atmospheric scattering.

GEOMETRIC REGISTRATION OF LANDSAT DATA

Geometric registration of Landsat data, whether to a map projection, to other Landsat scenes, or to data from other sources, involves two basic steps. The first step involves determination of the correct spatial location of a pixel in the output image-- the image to be corrected for registration. The second step is to determine the new value for the pixel in the output image. Spatial mapping transformations are usually applied to the data to determine the locations of output pixels. The locations for output pixels will rarely coincide to the locations for pixels in the input image, and thus pixel values for the output image will have to be interpolated for adjacent input pixels. This interpolation procedure is commonly referred to as resampling. Three commonly used resampling techniques are nearest neighbor, bi-linear interpolation, and cubic convolution. Nearest neighbor assigns a value to the output pixel which is equal to that of the nearest input pixel (Figure 8).

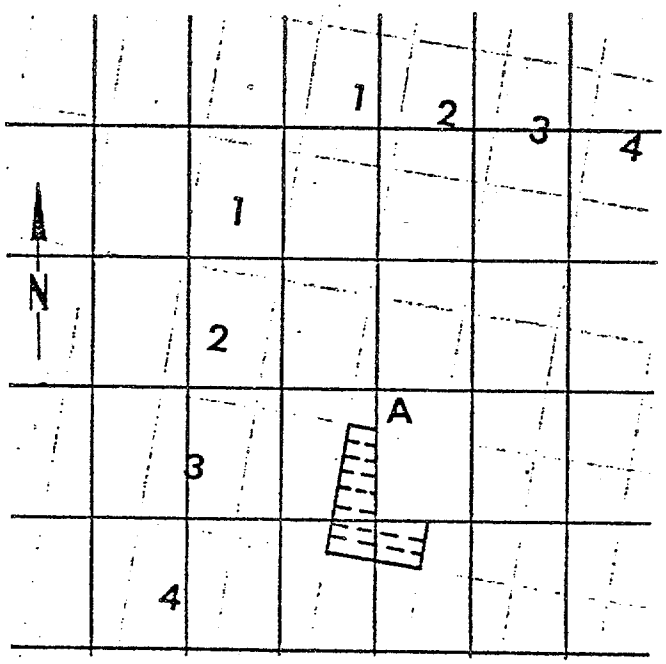


Figure 8. Nearest neighbor resampling. Pixel A is the pixel in the output image. Input pixel grid is skewed with respect to North. Value of Pixel A is determined from shaded, nearest pixel. (Rohde, 1977)

Bi-linear interpolation assigns values to output pixels by interpolation in two orthogonal directions. The values of input pixels on either side of the output pixel are weighted using the linear distance between the centers of the input pixels and the center of the output pixel (Figure 9).

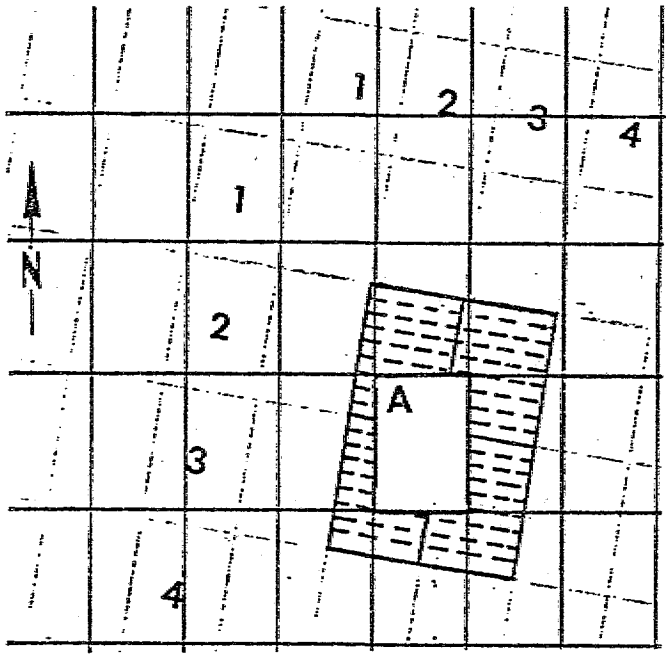


Figure 9. Bi-linear interpolation. Pixel A is the pixel in the output image. The value of A is determined from the weighted values of the surrounding 4 pixels in the input image. (diagram from Rohde, 1977)

The average value of the four weighted digital numbers of the input pixels is the digital number for the output pixel. Cubic convolution resampling assigns values to output pixels much in the same manner as bi-linear interpolation, except that the weighted values of 16 input pixels that surround the new pixel are used to determine the value of the output pixel.

IMAGE ENHANCEMENT

The general objective of image enhancement is to optimize display of the data to the analyst. Most image analyst-interpreters work with photographic images--film or print materials. The manner in which brightness values on a computer tape are recorded as densities on film is critical to an understanding of image enhancement. In fact, unless great care is taken to calibrate the photographic reproduction system, the results of carefully planned computer image enhancement may be spoiled by a poor job of film recording (Figure 10).

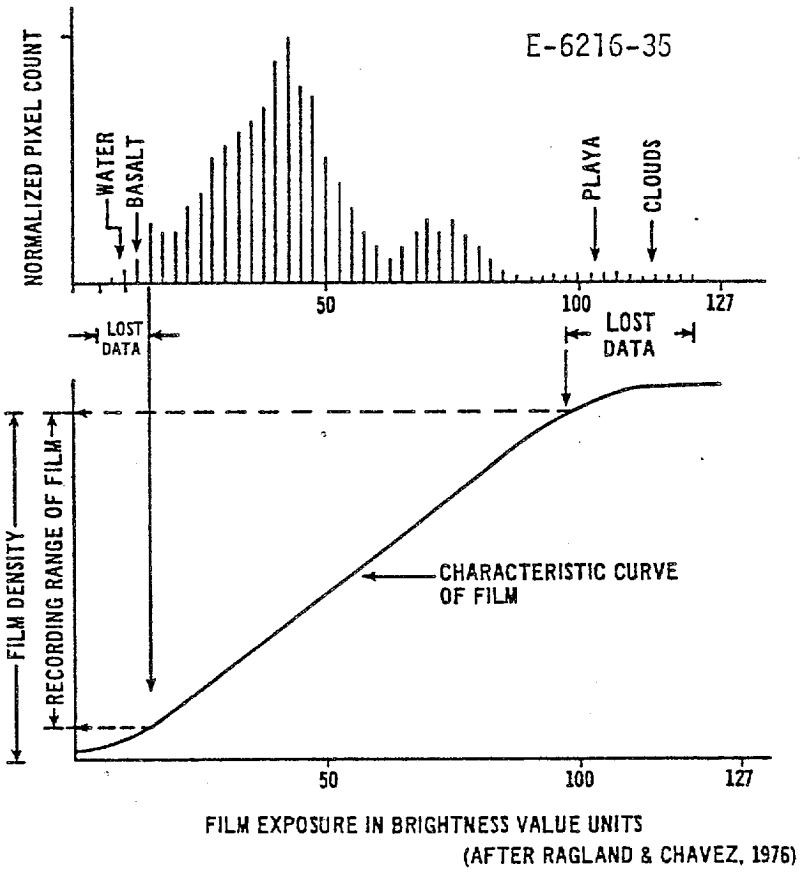


Figure 10. Undesirable relationships between brightness values on a CCT (input) and output film density.

The relationships shown in figure 10 are not desirable for a film recording system. Some data is lost, not by selection of digital processing parameters, but by the characteristics of the recording film. Ideally, the recording characteristics of the film system should not allow data to be lost (Figure 10). Either the range of brightness values should be restricted so it falls on the straight line portion of the film characteristic curve, or a different film recording medium should be selected which allows all brightness values to be recorded as discrete density levels on film (Lucas, Taranik and Billingsley, 1977).

CONTRAST ENHANCEMENTS

Linear Contrast Enhancement

The concept of linear contrast enhancement of Landsat digital data is shown in Figure 11. Most computer systems work in 8-bit mode

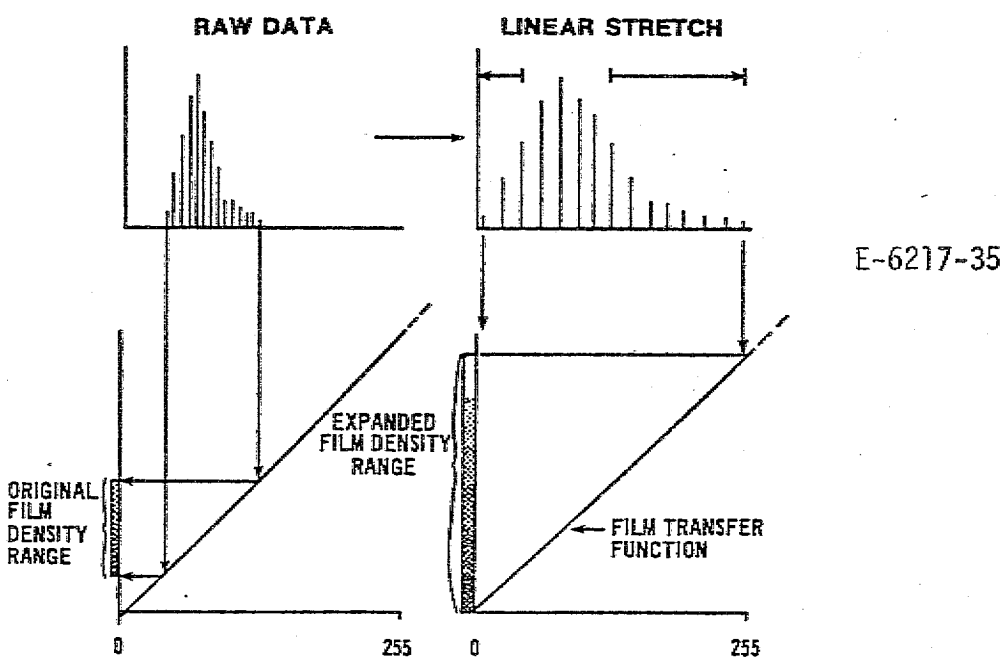


Figure 11. Concept of linear contrast enhancement

so Landsat data are scaled 0-255 prior to enhancement or they are distributed over this range during enhancement (Figure 11). Linear contrast enhancement is done by assigning new brightness values to each pixel in the scene in a manner expressed by equation 3.

$$BV_0 = \frac{BV_I - MIN}{MAX - MIN} \times 255 \qquad (3)$$

where:

BV_0 = Enhanced brightness value of pixel in output image

BV_I = Brightness value of pixel on CCT (input value)

MIN = Minimum brightness value parameter

MAX = Maximum brightness value parameter

Brightness value parameters are usually determined by an analyst, who determines what data is to be lost (truncated) by examining histograms or by interactively determining which data values are to be assigned maximum and minimum values on the output image. Sometimes automatic truncation limits are established using a rule that a certain percentage of the data are to be lost (truncated) on either end of the histogram. The EDIES products produced at EDC have brightness value parameters determined on an interactive multispectral analysis computer which allows the analyst to visually determine which picture elements will be lost (saturated to black or white) on imagery and the technique employed is described by Lucas, Taranik, and Billingsley, 1976. When the expanded range of brightness values is recorded on film the result is an expanded density range. Thus features in the scene are more easily distinguished because of the higher scene contrast. Note, if the slope of the film transfer function was increased for the raw data (Figure 11), these data would be recorded over an expanded film density range. This technique

is referred to as photo-optical enhancement, and it has been successfully applied to Landsat data (Lucas, Taranik, and Billingsley, 1977).

Non-linear Contrast Enhancements

The concept of a non-linear contrast enhancement is shown in Figure 12.

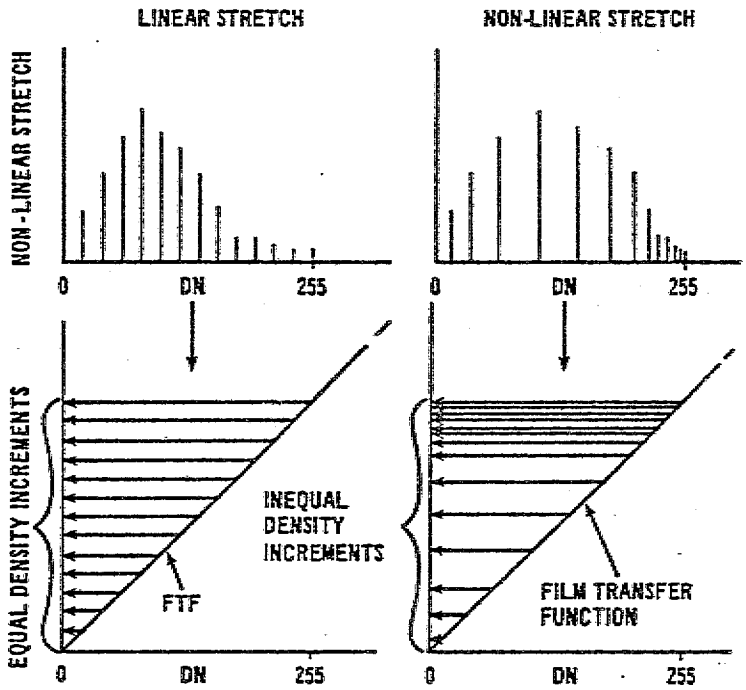


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Figure 12. Concept of non-linear contrast stretch

In non-linear contrast enhancement techniques an algorithm is applied to the original data which redistributes data values in a manner such that increments of scene brightness are inequally distributed over a range of 0 - 255. Some non-linear contrast enhancement algorithms which are employed are the following:

1. Piecewise-linear
2. Ramp Cumulative-distribution function (CDF)
3. Probability-distribution function
4. Sinusoidal
5. Gaussian
6. Power, logarithmic

As an example, the probability distribution function stretch spreads brightness values having the highest frequency of occurrence farthest apart and it compresses those values having the lowest frequency of occurrence. The non-linear stretch shown in figure 12 is a probability distribution stretch. Non-linear contrast enhancements can be extremely useful in the analysis and interpretation of imagery for geologic applications. In areas dominated by rock and soil cover for instance, the probability distribution function stretch can make subtle differences in rock and soil brightness more apparent, but at the expense of differences in brightness between playas and clouds and between basalt and water. In general use of non-linear contrast enhancement techniques is restricted by the scene dependency of Landsat data and by the application. A great deal of analyst judgement, and usually several iterations through the computer are required to produce the desired results. Non-linear contrast enhancements are not options on EDIES products for the above reasons, and probably these type of enhancements should be performed on an interactive analysis system.

SPATIAL FREQUENCY ENHANCEMENTS

Spatial enhancements are designed to enhance or supress boundaries between features which have subtle differences in brightness values. The concept of spatial filtering is shown in Figure 13. An example of spatial enhancement is the edge enhancement option that is employed by the EROS Data Center to produce EDIES products. The directional filter that is applied to the data is moved along each line and uses an eleven pixel window. This window is moved one pixel at a time along the line and a local average of the 5 pixels before and after the

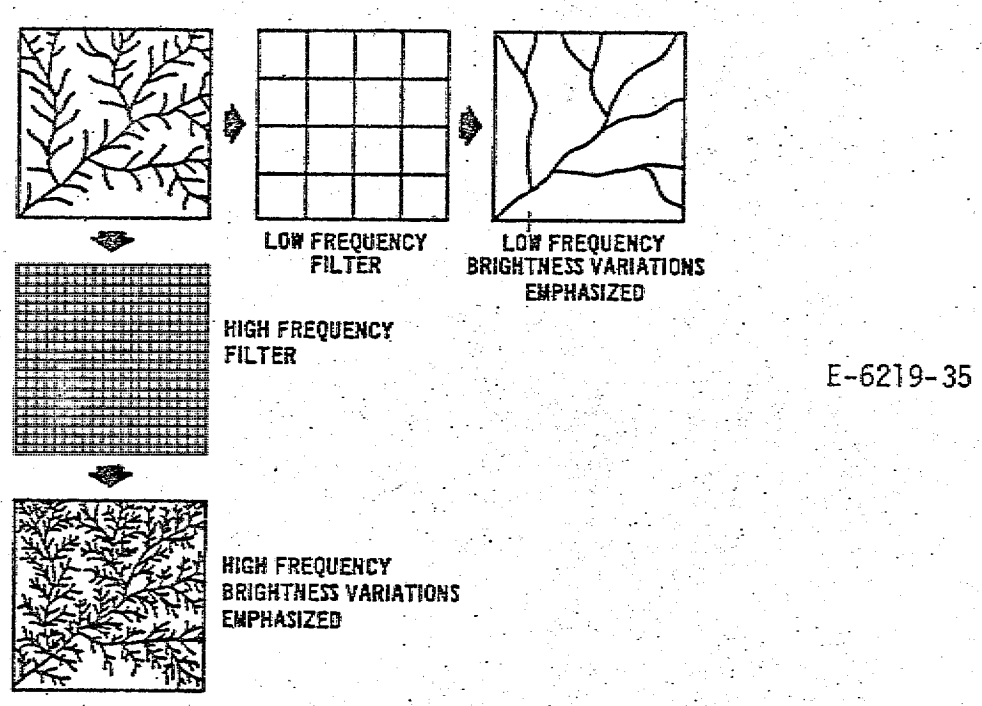


Figure 13. Concept of spatial frequency enhancement

pixel being examined, is determined. This local average is used to determine whether the pixel should remain the same, or should be enhanced in brightness. Pixels brighter than the local average become brighter and pixels darker than the local average become darker. Equation 4 shows how new values are computed for the edge enhancement performed on EDIES images.

$$DN_O = 2DN_I - A \qquad (4)$$

DN_O = Enhanced brightness value of pixel (output)

DN_I = Brightness value on CCT (input)

A = Local average from 10 pixels around pixel being examined for enhancement

This edge enhancement technique has the effect of producing a sharper image, but it may introduce artifacts into the data by producing shadows adjacent to features which have abrupt changes in brightness values. For geologic applications edge enhancement seems to work best for enhancement of drainage and landforms in areas of uniform cover.

RATIO ENHANCEMENTS

Single Scene Spectral Band Ratioing

The concept of spectral band ratioing is shown in Figure 14.

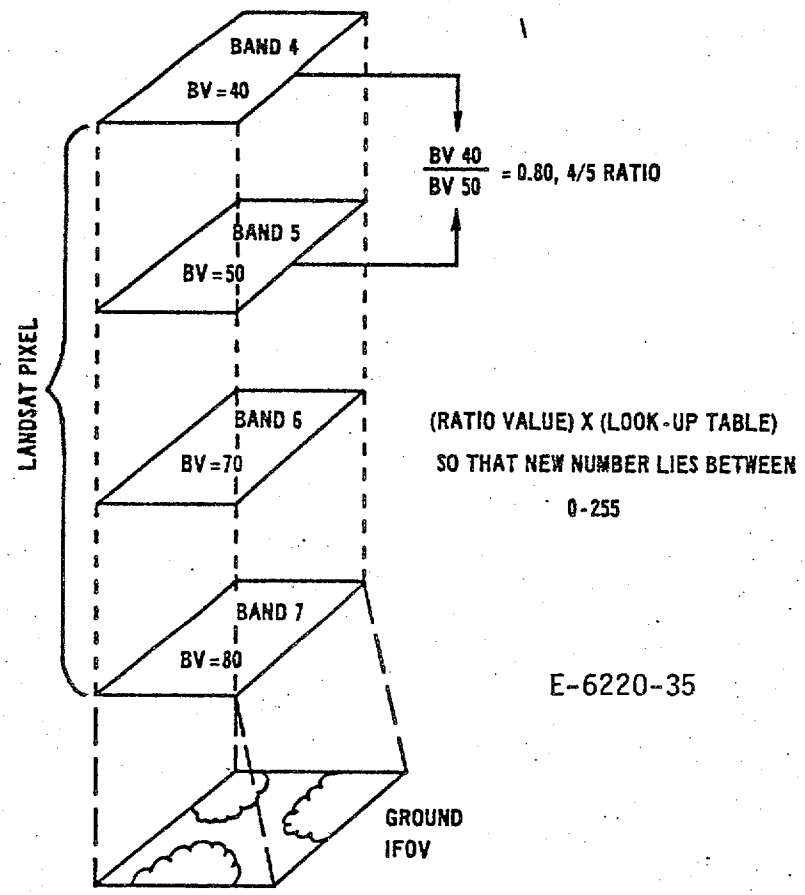
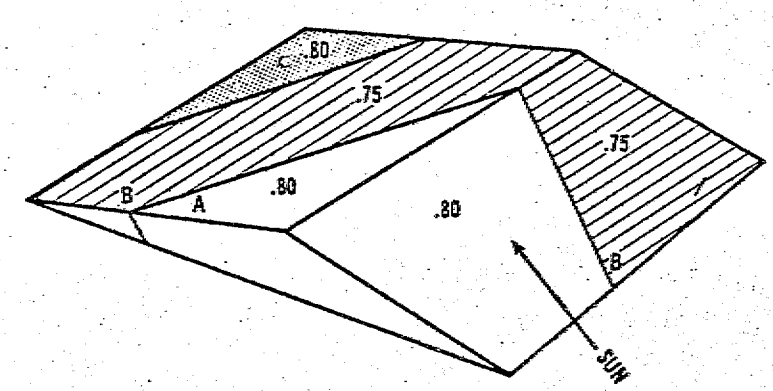


Figure 14. Concept of spectral band ratioing.

A ratio of two Landsat bands is obtained by dividing the brightness value in one band by the brightness value in another band, picture element by picture element throughout the scene. The ratio values obtained are usually multiplied by a look-up table so that all values will lie between 0 and 255. If Landsat data are not corrected for atmospheric effects, then the most practical ratios are band 4 divided by band 5 (4/5), band 5 divided by band 6 (5/6), and band 6 divided by band 7 (6/7). The rationale

for raticing is shown in Figure 15. Even though the two slopes in the



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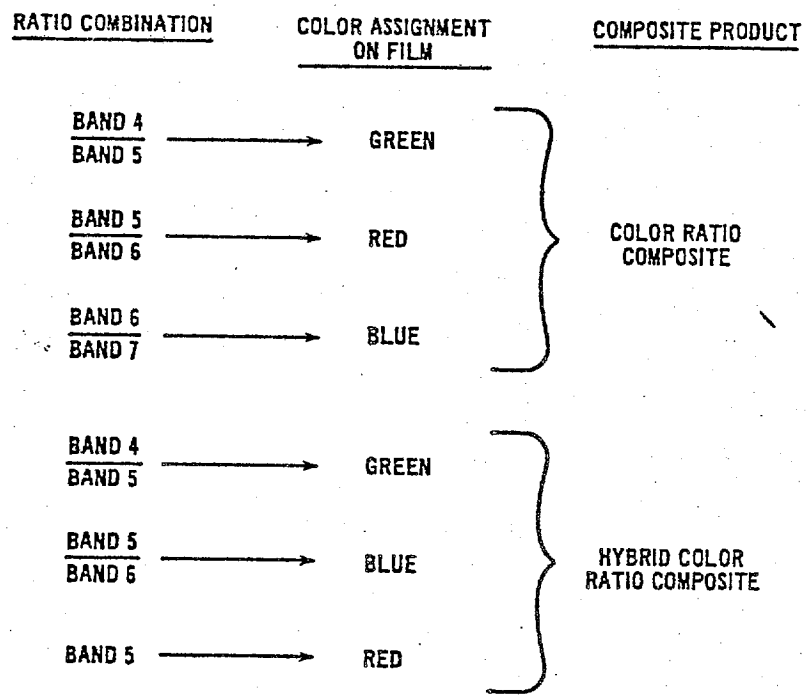
	BAND 4	BAND 5	4/5 RATIO
SLOPE FACING SUN			
UNIT A	20	25	.80
UNIT B	30	40	.75
SLOPE FACING AWAY FROM SUN			
UNIT A	16	20	.80
UNIT B	24	32	.75
UNIT C	32	40	.80

Figure 15. Rationale for ratioing

receive a different flux of electromagnetic radiation from the sun, and even though the same materials have different brightness values on the opposed slopes, the ratios of the brightness values are the same on either slope. Ratioing tends to reduce the effects due to topography and it tends to emphasize changes in brightness values between two Landsat bands.

Single Scene Hybrid Spectral Band Ratioing

Note on Figure 15 that if unit C was adjacent to unit A they would not be distinguished by a ratio, even though they were on the same slope and had vastly different brightness values. This problem can be overcome by combining a single Landsat band, which has not been ratioed, with the ratioed bands or combinations of ratioed bands. Some color combinations for use with ratios of Landsat bands are shown in Figure 16.



E-6222-35

Figure 16. Color combinations for ratio's of Goldfield area. Other combinations can be used depending on what is most appealing to the analyst.

TEMPORAL RATIOING

One useful technique for determining changes in landscape cover conditions over time is to perform a temporal ratio of the same Landsat band. For example, in Pocatello Idaho strip mine development was monitored using a ratio of two band 5 images acquired two years apart (Carneggie and Holm, 1976). On band 5 a high contrast exsits between bare ground and vegetation. On the temporal ratio new areas of bare ground appeared as bright areas. In areas where no change had taken place the ratio image had a uniform gray tone.

ARTIFICIAL COLOR ENHANCEMENTS

The Center for Astrogeology in Flagstaff, Arizona has developed a technique for displaying colors on Landsat imagery as they would appear to a human observer with normal color vision. The Earth's surface is displayed in color as if the Earth lacked an atmosphere and the observer was at orbital altitude. These types of images are often called "natural" color images as opposed to the "false" color images for standard Landsat products. Because Landsats 1 and 2 do not have a blue visible band, standard Landsat color products are printed so the green visible band (band 4) is blue, the red visible band (band 5) is green, and the invisible infrared band (band 7) is red. Artificial color images are developed from a computer produced blue band. This blue band is displayed as visible blue, the existing Landsat band 4 (visible green) is displayed as visible green, and the existing Landsat band 5 (visible red) is displayed as visible red on artificial color imagery. A schematic diagram illustrating how artificial color production is accomplished is shown in Figure 17. Raw Landsat data is corrected for atmospheric scattering. Then a 5/6 ratio is performed to identify pixels as belonging to soil-rock, vegetation, or water classes. An algorithm is then applied to the data in all spectral bands to determine the brightness for pixels in the new "blue" band (Figure 18). This technique is fully explained in Chavez and Mitchell, 1976.

Artificial color imagery is produced for the U. S. Geological Survey's Geologic Division personnel for use in regional geologic mapping, particularly in arid environments and in Alaska. On false color images (standard products), red rocks appear yellow-green so the Geologic Division has elected to have Landsat data produced so that such rocks would appear red, more like geologists would perceive them in the field. Geologists who are not skilled in remote sensing techniques could use "natural" color imagery more readily than false color imagery. The costs for processing Landsat data to artificial color format are considerable and must be considered in the light of the potential benefits.

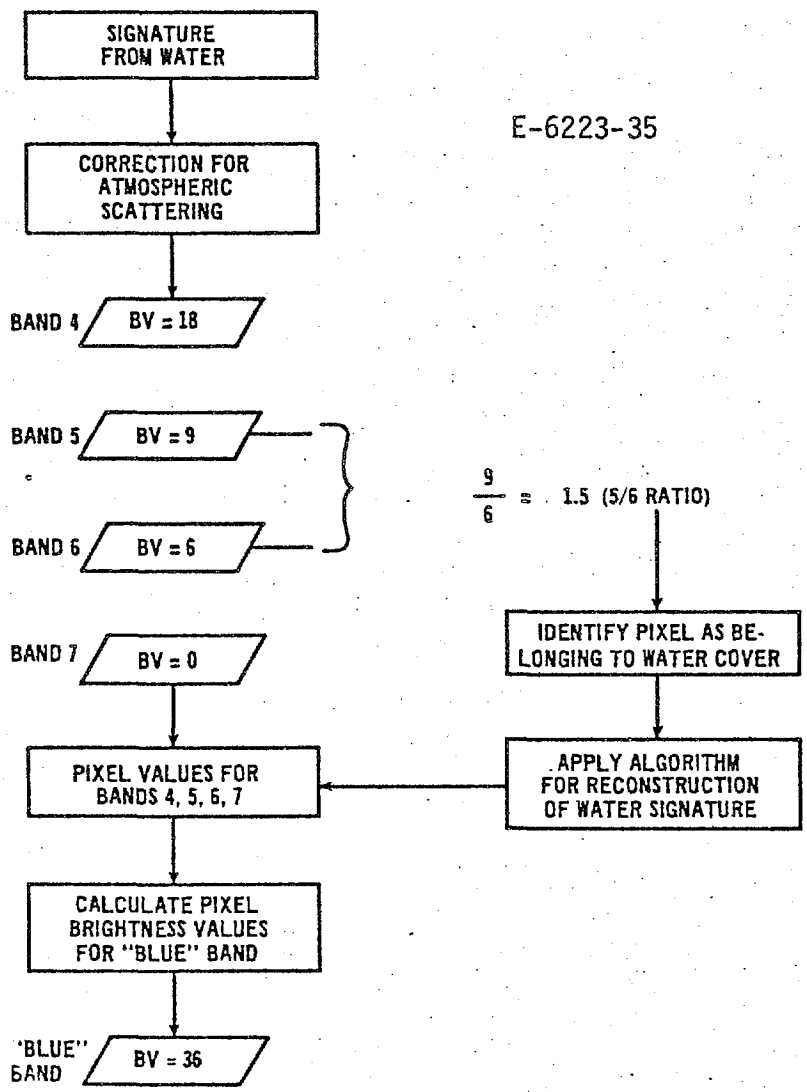


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Figure 17. Schematic for artificial color production

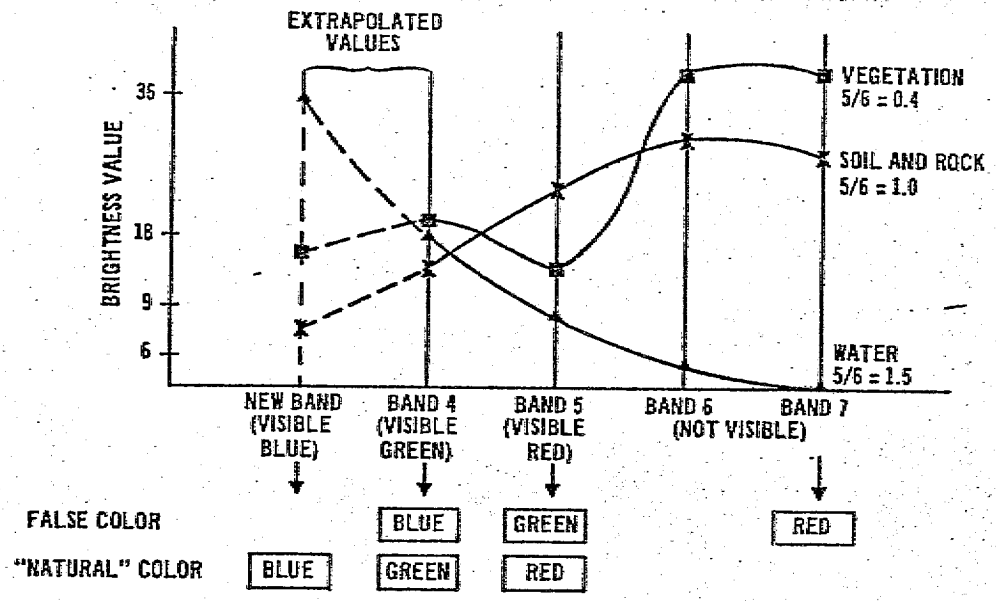

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Figure 18. Concept of artificial color production

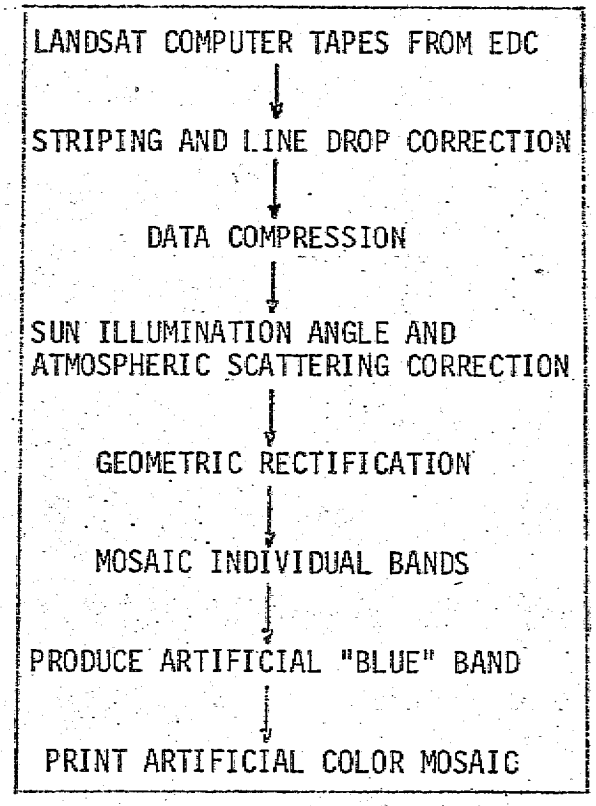


Figure 19. Development of electronic mosaic of the State of Nevada. Some of the processing steps used by Geologic Division in producing an artificial color mosaic of the State of Nevada from over 20 Landsat scenes. Master film transparency is about 5 inches by 9 inches.

IMAGE CLASSIFICATION

Image classification of Landsat 1 and 2 data involves both machine assisted delineation of multispectral patterns in four dimensional spectral space, and it involves identification of machine delineated multispectral patterns as representative of Landscape cover patterns. The first process is called multispectral analysis and the second process is called multispectral classification (Figure 1). Image data are not classified until an interpreter determines which spectral classes are representative of particular cover conditions. A geologist must then determine the relationships between cover classes displayed by the multispectral classification and the geology. Usually the type of geological information derived from an analysis of a multispectral classification is mainly related to lithology (Figure 1).

If an algorithm is employed to determine "natural" groupings of multispectral data in four dimensional spectral space, then the image is said to have been analyzed using an unsupervised approach. The clustering analytical processor described by Anuita (1977, p. 425) is a good example of this approach. If the analyst "trains" the analytical processor by selecting samples of classes to be recognized, then the image is said to have been analyzed using a supervised approach (Figure 20). The maximum likelihood analytical processor described by Anuita, (1977, p. 425) is normally used in a supervised mode.

The parallelepipid classification algorithm employed on the Image 100 at EDC is an example of a multispectral analytical processor that is used in a supervised approach. An analyst trains the computer on the

TYPES OF CLASSIFICATION TRAINING

- UNSUPERVISED – IDENTIFICATION OF NATURAL CLUSTERS OF DATA IN FOUR SPECTRAL DIMENSIONS USING ALGORITHMS

- SUPERVISED – DETERMINATION OF THE SPECTRAL LIMITS OF A SPECIFIED NUMBER COVER CLASSES THROUGH ANALYSIS OF SAMPLES OF THE CLASSES

CLASSIFICATION ALGORITHMS COMMONLY EMPLOYED

- PARALLIPIPID – DETERMINES WHICH PICTURE ELEMENTS FALL INSIDE A CLASSIFICATION SPACE DEFINED BY THE FOUR DIMENSIONAL SPECTRAL LIMITS OF A PARTICULAR COVER CLASS

- MAXIMUM LIKELIHOOD – DETERMINES WHICH PICTURE ELEMENTS MOST LIKELY BELONG A SPECIFIED CLASS FROM ANALYSIS OF THE VECTOR MEANS AND COVARIANCE MATRICES OF SAMPLES OF ALL CLASSES

E-6226-35

Figure 20. Common procedures used in image classification

multispectral limits (in four spectral dimensions) by positioning an electronic cursor over a particular cover type on a television screen. The computer then determines the spectral dimensions of the classification volume for that cover type (a four dimensional volume). The computer searches the multispectral volume for the entire scene and determines which picture elements fall within the classification volume. The picture elements which occur within the classification volume are said to be classified and they are usually identified by a color code on imagery or letter code on a print-out. The concept of the parallelipipid classification algorithm is shown in Figure 21. Note in Figure 21 that only three spectral band axes are shown for purposes of illustration.

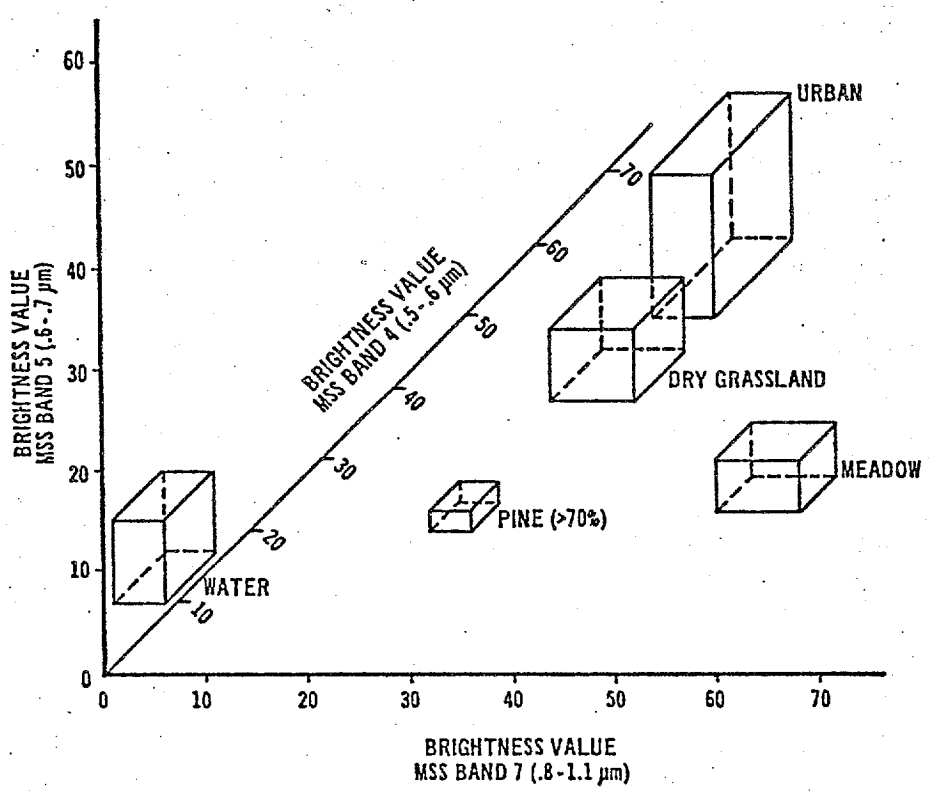


Figure 21. Concept of parallelipipid classification algorithm.

Image classification techniques have been little used when compared to the extensive utilization of enhancement techniques for geologic applications. The relationships outlined on Figure 1 partially explain why the classification approach has been little used in analyzing data for mineral and petroleum exploration. The classification approach provides mostly information on cover conditions and a geologist must interpret the lithologic significance of the classification before it can be used as part of an analysis of potential targets for exploration. The integration of spectral response by the MSS is shown in Figure 22.

E-6192-35

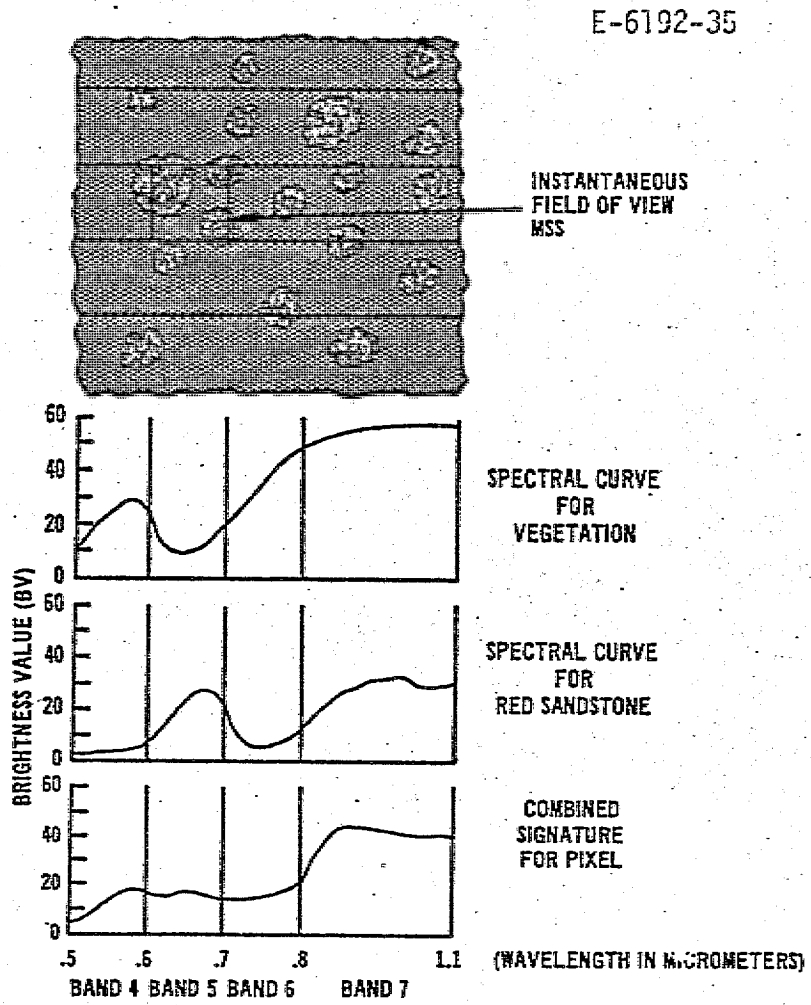
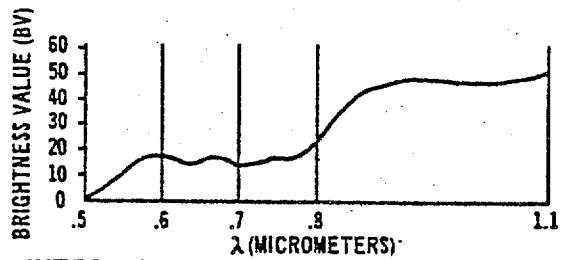
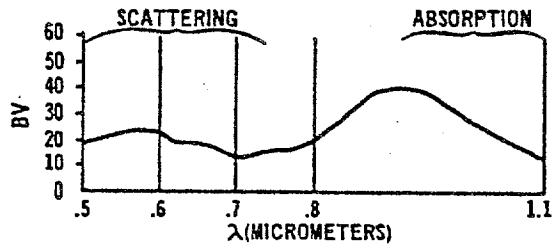


Figure 22. Integration of spectral response by the Landsat MSS. Atmospheric effects ignored.

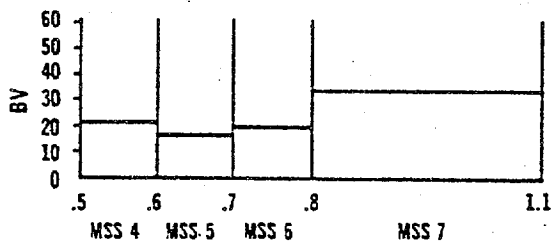
The effect of the atmosphere on spectral brightness values measured by the MSS is shown on Figure 23. It is absurd to expect that image



INTEGRATED SPECTRAL SIGNATURE FOR RED SANDSTONE AND VEGETATION



ATMOSPHERIC EFFECTS ON INTEGRATED SPECTRAL SIGNATURE FOR RED SANDSTONE AND VEGETATION



E-6193-35

SPECTRAL SIGNATURE AS RECORDED BY LANDSAT MSS

Figure 23. Atmospheric effects on spectral signature recorded by the MSS on Landsat

classifications will replicate geology mapped at large scales. 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) interpolating between rock exposures, (2) using rock fragements 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 (Taranik and Trautwein, 1977, p. 774). In spite of the foregoing, the combination of plant, soil, and water associations with geologic units, and sometimes the unique spectral characteristics of lithologic relationships can allow classification procedures to be successfully applied to Landsat data for targeting of ground-based geologic investigations. Successful application of the classification approach requires a thorough understanding of the remote sensing system, the machine analysis procedures involved, and an appreciation for what cover conditions are being displayed by the multispectral classification. For additional reference materials on the Landsat System the user of this material should consult Taranik, 1977.

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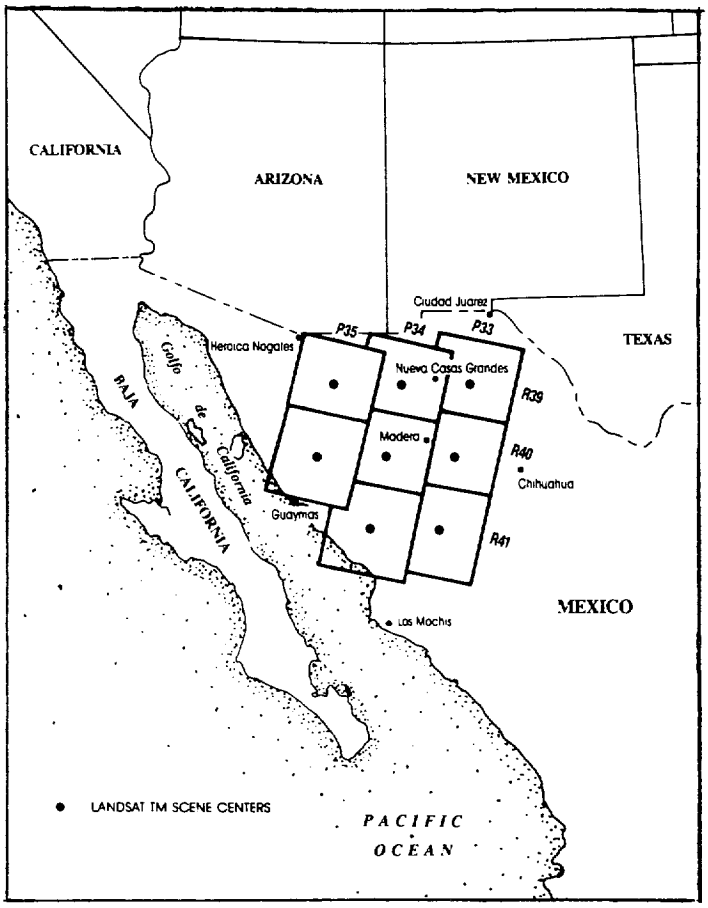
LANDSAT THEMATIC MAPPER IMAGE PACKAGE

OF NORTHWESTERN MEXICO

FOR

MINERAL EXPLORATION



EARTH SATELLITE CORPORATION

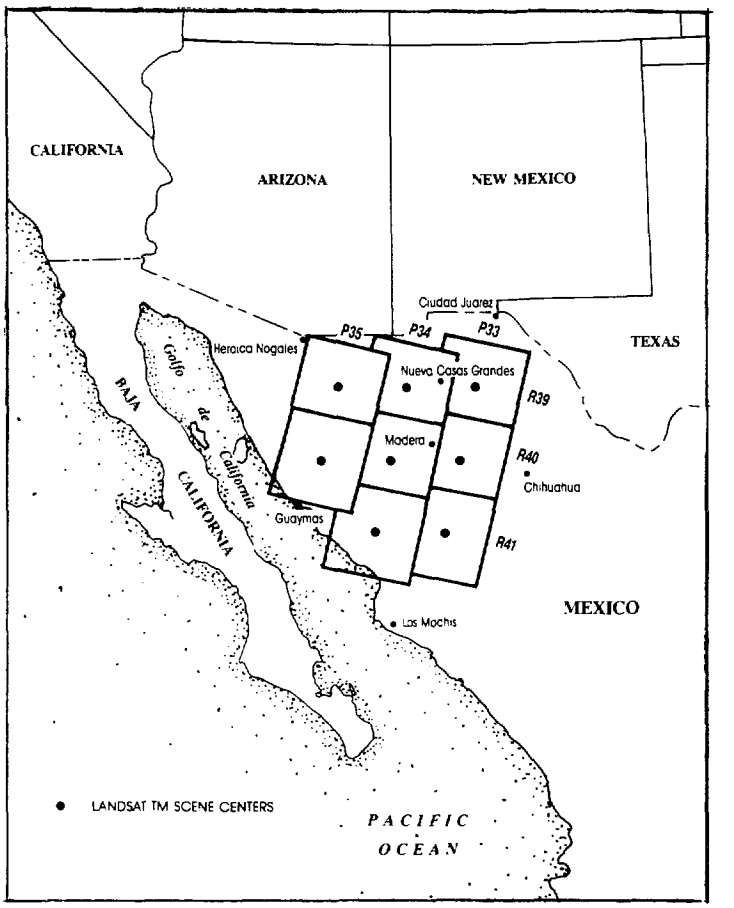
6011 Executive Blvd., Suite 400
Rockville, MD 20852 USA
Phone: (301) 231-0660

LANDSAT THEMATIC MAPPER IMAGE PACKAGE

OF NORTHWESTERN MEXICO

FOR

MINERAL EXPLORATION



EARTH SATELLITE CORPORATION

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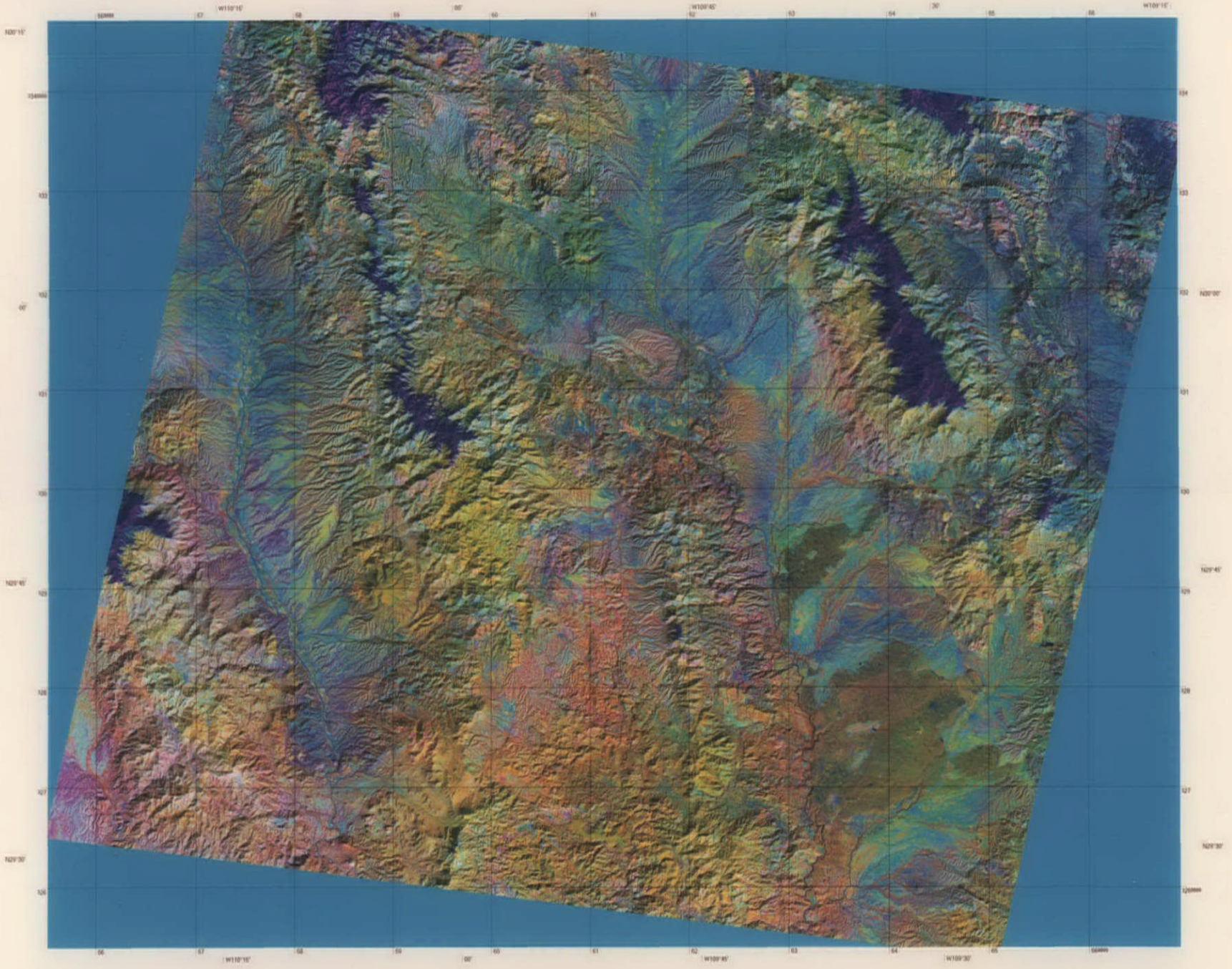
Phone: (301) 231-0660

Aconchi, Mexico



Grid: 10,000 meter UTM, Zone 12, World Geodetic System 1972 Ellipsoid

Projection: Transverse Mercator
WGS-72

Landsat Thematic Mapper resolution 28.5m pixels. Image compiled to identified map features [illegible] geometrical error is [illegible] meters. The representation of international [illegible] of necessarily [illegible]

EARTH SATELLITE CORPORATION (EARTHSAT)
Michael G. Dowling, Manager
6011 Executive Boulevard, Suite 400
Rockville, MD 20852 USA
Phone: (301) 231-0660 Fax: (301) 231-50220
Telex: 248618 ESCO UR

Landsat TM (1/4) scene of Aconchi, Mexico processed utilizing proprietary GEOVUE™ technique. Image was geocoded to 1:250,000 topographic maps, grid in 10 km squares.

LANDSAT THEMATIC MAPPER IMAGE PACKAGE

OF

NORTHWESTERN MEXICO

FOR

MINERAL EXPLORATION

by

Earth Satellite Corporation
6011 Executive Blvd, Suite 400
Rockville, MD 20852 USA
Phone: (301)231-0660

1991

Contact: Michael G. Dowling

LANDSAT THEMATIC MAPPER IMAGE PACKAGE OF NORTHWESTERN MEXICO FOR MINERAL EXPLORATION

Background

Mexico is one of the best mineralized countries in the world and has been actively mined for more than 400 years. The image package covers the northeastern and northwestern portion of the states of Sonora and Chihuahua, respectively. The state of Sonora has geology and mineralization very similar to that found just to the north in Arizona. Travelling east towards Chihuahua there is a significant change in geology and mineralization that is quite unlike anything found in North America and contains the Sierra Madre Occidental type origin deposits.

While all of Mexico is covered by excellent series of topographic quadrangle maps at 1:50,000 and 1:250,000 scales, the geologic series maps of the same scale are nothing more than photogeologic maps of the major geologic units. Also, there are virtually no background studies published to support the existing geologic map series, nor is there detailed information on production, grade and deposit origin of existing mining operations.

The primary challenge to the field geologist, who must evaluate hundreds of thousands of square kilometers of potential ore deposits, where there are a multitude of readily visible mineralized areas, is how to limit the huge number of targets. In a region with this type of mineralization, the differentiation of mineralized and barren geologic features is key to minimizing exploration costs.

The proposed image package is specifically designed to provide the explorationist with a distinct competitive edge in identifying quality targets to implement and develop regional exploration plans. This package will help to define more precisely high quality exploration targets which may not be discernable through more traditional exploration techniques.

LANDSAT THEMATIC MAPPER IMAGE PACKAGE OF NORTHWESTERN MEXICO FOR MINERAL EXPLORATION

Scope

The attached location diagram (**Figure 1**) outlines the proposed area of coverage. Covering parts of the Sonora and Chihuahua provinces of Mexico, this region is host to a large number of porphyry copper deposits and related mineralization. Some of the larger mines contained within this area include: Cananea, Macozari, El Barrigon, Pilares, Santa Rosa and La Caridad.

Eight (8) TM scenes, each covering an area approximately 180 x 180 km will be provided in this package. Each scene will be individually enhanced using EarthSat's **GEOVUE™** interactive enhancement (**see attached image, scale approximately 1:400,000**). This recently developed proprietary algorithm utilizes six spectral bands of the Landsat TM data to maximize discrimination of structure, lithologic distinctions and zones of alteration, while minimizing the masking effects of vegetation. Spectral wavelengths covered by Landsat TM data range from the visible to near infrared. The visible wavelengths are particularly useful for discriminating between different iron mineral assemblages, while the near infrared wavelengths allow for the discrimination of clay mineral assemblages. This is extremely useful in the porphyry copper environment with its associated alteration zones.

In addition to the **GEOVUE™** enhancement, another complementary enhancement technique will be provided for each of the scenes. This enhancement will be a color composite of the three least correlated spectral bands, with a Decorrelation (Decor) stretch applied to enhance the contrast. This enhancement will be spatially filtered to provide maximum structural information.

All of the images will be geocoded (rectified) to existing topographic quadrangle maps at a scale of 1:250,000. Mexican geological maps are also available at this scale. Geological and logistical information can be transferred directly from the geocoded images to your map base. We will also generate clearfilm overlays to each of the images which will provide a compilation of mine locations, names, deposit types and major cities to aid in exploration.

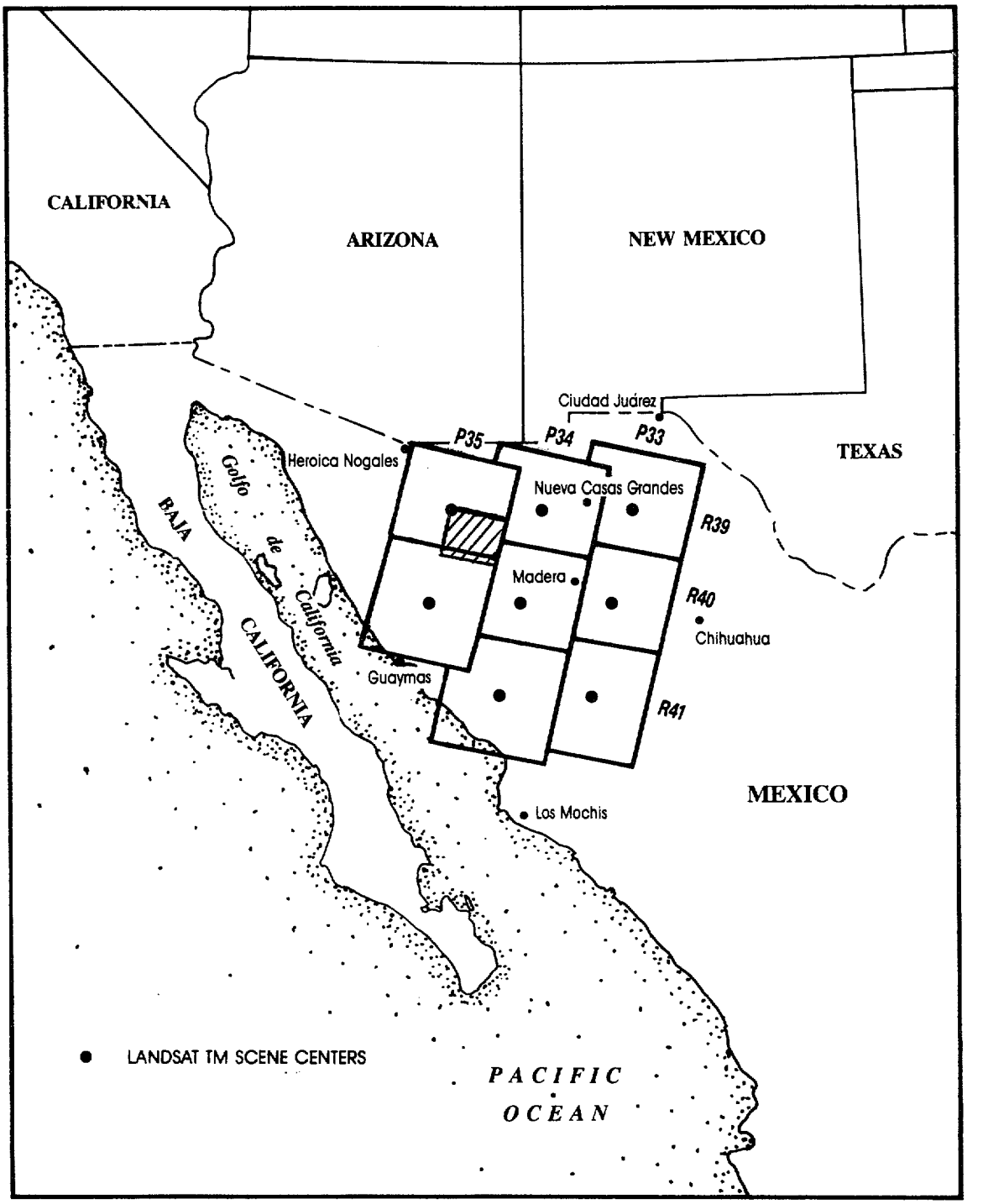


Figure 1: Sketch map of coverage for Mexico image package.

LANDSAT THEMATIC MAPPER IMAGE PACKAGE OF NORTHWESTERN MEXICO FOR MINERAL EXPLORATION

Study Deliverables

The study will consist of a set of rolled satellite image maps and a companion set of clearfilm overlays:

Deliverables:

Landsat TM Images:

(8) GEOVUE 1:250,000
(8) Decor 1:250,000
(8) GEOVUE 1:1,000,000
(8) Decor 1:1,000,000

Clearfilm Overlays:

(8) Overlays matching the Landsat TM images with mine locations, names, deposit types and major cities. Additionally, there will be location map cross-hairs matching the 1:250,000 scale Mexican map series.

LANDSAT THEMATIC MAPPER IMAGE PACKAGE OF NORTHWESTERN MEXICO FOR MINERAL EXPLORATION

Financial Arrangements

This will be a non-proprietary data package, available for purchase by any interested party. The target price for the image package is $30,000 for one complete set of deliverables. This cost is less than the raw data costs to your company if you chose to purchase the TM data yourself. Enlargements to different scales will be available at reproduction costs. Pre-committing organizations will pay only $25,000. One half of the cost will be due at the time of agreement and the remaining half upon delivery of the package. Due to the high data costs involved in this study, EarthSat requires four (4) organizations to pre-commit before data acquisition and image processing is initiated.

Additional copies are available for internal use at $7,500. Additional copies for Joint Venture Partners are $12,500 each.

_____
Date

Mr. Michael G. Dowling
Earth Satellite Corporation
6011 Executive Blvd., Suite 400
Rockville, MD 20852
U.S.A.
Phone: (301) 231-0660
Fax: (301) 231-5020

Dear Mr. Dowling:

_____ wishes to purchase the **Landsat Thematic Mapper Image Package of Northwestern Mexico for Mineral Exploration** for $25,000. It is understood that $12,500 (50%) is due upon this agreement. The remaining payment of $12,500 is due upon delivery of the package in our offices. Deliverables are as defined in the proposal.

Invoice Address	**Shipping Address**
_____	_____
_____	_____
_____	_____
_____	_____

Sincerely,

_____
Signature

_____
Title

Date

ASARCO

Copy FTG 3/28/77

Southwestern Exploration Division

March 24, 1977

Mr. G. Bryan Bailey
Salt Lake City Office

LANDSAT

Dear Bryan:

Attached please find Jim Sell's resume of the Landsat Imagery Conference convened by you in Salt Lake City. Mr. Sell has written a number of conclusions and recommendations with which I am in complete accord. Regarding enhanced imagery study, the relative lack of bedrock in southeastern Arizona combined with the presence of post-mineral volcanic rock cover within the mountain range suggest that other areas would be better suited to such a study in light of the $2,000 to $3,000 cost per image.

Very truly yours,

F. T. Graybeal

F. T. Graybeal

FTG:lb
Att.

cc: WLKurtz

COPY TO 3/29/77 JHR WLK

ASARCO COPY TO of Charles Barclay memo

Southwestern Exploration Division

March 23, 1977

TO: F. T. Graybeal

FROM: J. D. Sell

Landsat Imagery Conference
Asarco Group
March 5-6, 1977
Salt Lake City, Utah

Conclusions and Recommendations:

My general consensus is that random marking of Landsat images results in unresolvable patterns unless comprehensive known geologic constraints are monitored. Only in rare cases can rock types be differentiated except into very broad groupings. Mineral districts are often in areas of complex structural and stratigraphic position which is mainly unresolvable by present image parameters whereas broad uplifts and long throughgoing structures (Rocky Mountain Trench, etc.) and stratigraphy (Colorado Plateau beds, etc.) are outstandingly traceable. Present discrimination parameters give little clue as to present mineral district location or alteration groupings. Man-cleared activities often exhibit more visible characteristics.

In generalities the far-away to close-up approach to marking Landsat imagery may be useful in indicating zones of intense and long-history deformation capable of hosting districts. Projection and extension of these zones into areas of cover or incomplete mineral inventory control may be useful for a renewed and comprehensive evaluation by field parties.

Detailed evaluation in areas where individual geologists have a strong philosophy of the district often indicates features of interest which had a previous low priority. Resolvement of these often adds an insight to the problems at hand, but to date has not added to the rock-in-the-box.

The present state-of-the-art of image enhancement appears to only clarify the broad picture which is non-decipherable as a mineral district control.

Continued involvement will heighten the awareness of the individuals but until image parameters are drastically improved it is questionable as to the resolvement of the nitty-gritty of explorationists.

The continuation of the Landsat Image Conference-Enhancement Section, as expressed by T. C. Osborne, should clarify the state-of-the-art for the exploration group. Utilization of various physiographic-geologic areas will again clarify and distribute awareness to the individuals as to the prospective benefit of the images for the various districts in their areas and problems. I would hope that a handbook, for internal use, be compiled and made available to all offices as a prelude to the use, benefits, nitty-gritty, costs, and varieties of Landsat Images and Enhancements, for continued district involvement beyond the general company review.

Conference:

The Asarco Landsat Imagery Conference convened in Salt Lake City on Saturday, March 5, 1977, with the final discussion concluded the following day. In attendance were Jerry Biery (Knoxville), D. H. "Ollie" Olsen and Don G. MacIntyre (Vancouver), Larry Applegate (Spokane), Chuck Beverly (Denver), myself, and the conveners, G. Bryan Bailey (Salt Lake City) and J. J. Collins (Consultant).

Mr. Collins passed out the memos submitted by the offices as follows:

1) Notes on Interpretation of ERTS Imagery Location 59-18 by P. Glehn Curtin (McMillan Project, Canada).

2) Northwest Territories, Coppermine River Area, Landsat Image 55-13 (Canada), by R. E. Gale.

3) British Columbia Landsat Images 47-25 and 46-25 Interpretation, by D. H. Olsen.

4) Northwest Territories, District of Mackenzie, Yellowknife Area, NTS 85, Landsat Interpretation by D. G. MacIntyre.

5) A geology map mylar of the Cumberland River Imagery by Jerry Biery.

6) North Central Nevada Landsat Interpretation by G. Bryan Bailey.

7) Landsat Imagery Interpretation, Limpopo Mobile Belt, South Africa, Rhodesia, Botswana, by C. A. M. Ferreira.

Collins announced that the program would consist of a review of each image of the group. This was undertaken by projecting the image on a clean sheet of paper at the same scale of the worked image (approximately 1:250,000), with the group then marking the linears, curvilinears, and circular patterns as seen by the group at: a) a distance of twenty feet (equal to about 1:1 million scale), b) a distance of ten feet (equal to about 1:500,000 scale), and finally c) the image distance (the same as viewing at your desk; i.e., 1:250,000 scale). The markings were placed with no restraint other than being visible in some form. The marking color was varied according to the distance viewed. After the three viewing distances were marked (see the one made for my Phoenix-Tucson Image 39-37), the lights were turned on and the masterpiece of coloration-contortion pattern exposed to all. The principal investigator of the image shown did not enter the marking contest, but now compared his overlay with that constructed and offered tid-bits of information, clarification, and any thoughts on interpretations and exploration guidelines. This was followed by a general discourse by the group and principal investigator.

The main points as gathered by me are as follows:

A) Southeast Alaska by L. Applegate. Intersection of linears, convergences of linears, and numerous converging large and small, nested, circular patterns, strongly reinforce areas to be checked when known

to contain some metallization. One particular grouping contains some ninety percent of the known districts, while outside this grouping the two other occurrences appear to be at convergence points of three or more linear patterns.

B) Cumberland River, Tennessee by J. Biery. Patterns as found in the Alaska image were duplicated. Biery pointed out that large features and, more or less, regional structure and stratigraphy could be seen (see mylar of area). The 100 million tons of 5-6% Pb-Zn at the Elmwood district are apparently at the north end of the Beechgrove linear (which the group had noted but could not separate in significance to a number of others), which is near the Cumberland River. Biery points out that northeast trends (linears) are good district controls, while the mines are on north-south trends (linears). Possibly the known districts are on curvilinears (i.e., Cumberland River) intercepted by north-south linears. Biery further pointed out that stratigraphy and carbonate-magnesium zonation are necessary criteria and this is only weakly noted or unavailable on ERTS imagery.

C) San Juan, Colorado by C. Beverly. The "far away" basic pattern is continued and reinforced by the closer, more detailed analysis. This factor undoubtedly indicates continued structural control or activity over a period of time. Detailed analysis may, and does, indicate older structures partially and continually reactivated which may, as at the northwest-trending Platoro-Summitville lineament, be a real guide to mineralized intrusive zones. As Beverly pointed out, the several mile by ten mile altered zone at Alum Creek-Summitville is not readily distinguishable except by prior knowledge. Numerous other intersections were noted which have no apparent district control.

D) Phoenix-Tucson, Arizona by J. Sell. As shown by the attached group work sheet, a large number of linears, curvilinears, and circles were marked. J. J. Collins suggested more attention to the Globe-Miami zone and the Silver Bell zone and the notations are strongly favored in those areas. Five bright spots were outlined in the Sacaton area. In the discussion period J. Sell suggested that it is a near-impossible task to confirm most of the lines either by detailed analysis of available mapping or by new ground-truth mapping. Of the five bright spots in the Sacaton area, one is the Sacaton deposit, one is a large cleared area in alluvium, another in undisturbed desert, and two in the adjacent mountain ranges. Of the numerous intersections, none were discriminated as being the loci of deposits unknown to the participants (i.e., Blackwater, Posten Butte, Vekol Hills, and Lakeshore). The subtle clue at San Manuel (a block-cave hole is visible) is along a long, persistent linear going southerly from Roosevelt Lake through Devils Canyon and beyond. Lakeshore is near a long linear noted by the "far away" look but not confirmed up close or with additional intersection, while Vekol Hills is beyond a short linear with no others nearby. Whether San Manuel, Posten Butte, Blackwater, Lakeshore, Vekol Hills, and Sacaton would be found by today's checking along all intersections deemed important (which our group could not reach any conclusion as to criteria of discrimination) remains a moot point, but most agreed that these would not have been found even by ground-

truth checking unless a large amount of geologic thought-concept implementation was input into the follow-up program. As such, alteration discrimination and resolution problems are still "down the road" for image interpretation.

E) Yellowknife, Canada by D. W. MacIntyre. (See report submitted.) The major separation of Archean-Proterozoic-Paleozoic was marked by major linear structural zones and/or tonal resolution as found by the group. Also found was an area that turned out to be a greenstone area but a second greenstone belt was missed. The great Yellowknife District is only a part of the structural zone as outlined and a number of similar areas were noted which to date do not contain a significant district. Several tonal zones, including "Z" structures, mapped by the group turned out to be old timber burn areas. Overall the intensity of linears may be helpful in looking for new districts, especially where cutting greenstone belts, which apparently can be mapped by careful evaluation.

F) Southeast British Columbia, Canada by D. H. Olsen. Again a large number of lines were placed on the worksheet but no discrimination could be made as to values. The major mine (district) of Sullivan is marked by a zone intersection of north-south and east-west with the Rocky Mountain Trench structure nearby. Olsen, see report, noted many features which could be (and were) readily misidentified as to their significance (old clear-cut logging areas, etc.).

G) Northcentral Nevada by G. B. Bailey. In the group exercise a very large number of linears and nested circles were found including two areas which had the same characteristics as the Creede caldera of Colorado. Bailey's interpetation was not as complex, as he had primarily attempted to discriminate between alluvium and bedrock, as this would be of prime interest to field parties. He was partially successful but included a large area of low-lying tuff units as alluvium. He had also plotted all the mining districts, which have been available for some time by the Nevada Bureau of Mines, and by visual inspection they aligned into three rather distinct bands. In overlaying the district pattern over both the group linears and the Nevada geologic map (at the same scale) it was suggestive that our most intense zones were again covering the main mineral district bands. J. Biery pointed out that a color pattern on the Nevada geologic map was also in incident with the mineral bands.

In the general review that followed numerous questions were brought up but little resolution to the questions-problems was attained.

Bailey Dispersed several papers and reprints:

1) Geological Remote Sensing from Space; a report of the Ad Hoc Geological Committee with recommendations for a Geosat Program (Workshop in Flagstaff, Arizona, May 10-14, 1976).

2) The Geosat Committee, Inc.; a report by A. A. Brant, President. Mr. R. L. Brown of Asarco is one of the Directors. Mr. G. Bryan Bailey is the sub-chairman of the Porphyry Copper Group which is a part of Leo J. Miller's "Mineral" Committee of the Geosat Workshop Working Groups.

3) Geofractures and Fracture Trace Analysis by Nigel Press and Wim Kampschuur of Nigel Press Associates.

4) GeoImages, Inc.; a brochure of services and price list of one of the independent companies which do enhancement of Landsat Images (this group is apparently favored by Asarco to do such services).

For continued expansion of the Landsat exercise, the following parameters were noted for clarification of the image:

a) No cloud cover

b) Minor snow cover

c) Review all four bands to obtain maximum data

d) Sun angle is important depending upon area and use

e) Time of year is important depending upon area and use

Each division representative was asked to select one image for workover by the GeoImages, Inc. through their package Landsat Enhancement #1 (between $2,000 and $3,000 per image). I stated that a discussion would be needed to clarify the area, but that I favored using the same area as had been worked on in the present exercise (i.e., image 39-37, Phoenix-Tucson, or image 46-33, Yerington) in order to compare the images and attainable data between the present conference and the future, enhancement, conference.

Mr. G. Bryan Bailey stated that a memo should be sent to him on the meeting, its utilization and usefulness, and recommendation of the conference and the future enhancement conference.

This memo should serve that purpose.

James D. Sell

James D. Sell

JDS:lb
Attachments & Reprints with File Copy only
& in Map File (Drafting)

cc: WLKurtz

ASARCO

Rocky Mountain Exploration Division
Stephen Von Fay
Exploration Manager

March 11, 1977

Mr. G. Bryan Bailey
Exploration Department
ASARCO Incorporated
3422 South 700 West
Salt Lake City, Utah 84119

Dear Bryan,

Thank you for the memo of March 9th and copies of memos dated September 2, 1976 and December 7, 1976. This is the first time I had seen them which is why I raised a few nebulous questions at the meeting. As my memo of March 9th points out I thought we did accomplish a great deal in Salt Lake on the initial phase of Landsat evaluation. I look forward to interpreting the enhanced imagery.

Very truly yours,

Chuck

C.E. Beverly

CEB:slr

bcc: gDSell

JDS
I know you are interested in these kinds of things so why not sign up!
CES

FIRST ANNOUNCEMENT

The Association of Exploration Geochemists

7th INTERNATIONAL GEOCHEMICAL EXPLORATION SYMPOSIUM

DENVER, COLORADO APRIL 16-20, 1978

Technical Sessions

A three-day program of technical sessions is planned. The Symposium will be held at the Green Center on the campus of the Colorado School of Mines in Golden, Colorado, a suburb of Denver. The Symposium, sponsored by The Association of Exploration Geochemists, is planned for April 16-20, which is during the week before the Canadian Institute of Mining and Metallurgy meeting to be held in Vancouver, Canada, so that Symposium attendees from outside North America will be able to attend both meetings in one trip. The Organizing Committee will be soliciting papers in English on any phase of exploration geochemistry that would be of interest to an international audience. The proceedings of the Symposium will be published in a special volume.

Field Trips

Several geochemical laboratories in the Denver area will be open for tours during the Symposium. In addition, several one-day field trips are planned to mines and exploration projects in Colorado where geochemical surveys have been undertaken. If there is sufficient interest, an escorted field trip of about 1-week duration will be planned to visit porphyry copper and other types of deposits in Arizona and New Mexico. Emphasis will be on those deposits and areas where geochemical studies have been undertaken. Other geochemically-oriented trips to other parts of the United States may also be possible.

Non-technical Activities

The Denver-Golden area abounds with non-technical attractions related to Colorado's mining days as well as to its current position as the business, technical, cultural, and educational center of the Rocky Mountain West. There will be a large selection of personalized activities and tours available in Golden and Denver and in the nearby mountains, with escort service and transportation provided for Symposium attendees, their spouses, and guests.

Other Information

A circular describing details on submission of papers, housing, non-technical activities, and field trips, as well as a questionnaire to aid the Organizing Committee in planning the Symposium, will be sent to those persons who FILL OUT AND RETURN THE APPLICATION FORM GIVEN BELOW. To save mailing costs, the Organizing Committee would appreciate your circulating this announcement to your colleagues.

DETACH FORM ALONG THIS LINE AND MAIL

M.A. Chaffee, Secretary
Organizing Committee
7th International Geochemical Exploration Symposium
U.S. Geological Survey
5946 McIntyre Street
Golden, Colorado 80401 U.S.A.

Please place my name on the mailing list to receive further details regarding the 7th International Geochemical Exploration Symposium to be held in Golden, Colorado, U.S.A., in April 1978.

Please check appropriate boxes.

- ☐ I (definitely plan to attend) (may attend) the Symposium [strike out inappropriate words]
- ☐ I plan to submit an abstract and present a paper
- ☐ I am interested in field trips
- ☐ I am interested in non-technical activities

Name _____
Organization _____
Address _____

MARCH 9, 1977

Dear Jim

Just a quick note to say Hi — Thanks again for all the good discussions at Salt Lake. Skiing was fantastic and I survived the 25-30 falls and spectacular blips that one encounters from skiing Alta.

I skied part of day w/ JJC and he had no comment on the meeting. I skied the rest of the time w/ Lloyd James who had a "vacation day" and he feels about like you & I about GBB. He's had several run-ins etc. Of interest was Lloyd's comment he heard from Leo Miller "GB is an outstanding young man"... sound familiar ?? Oh well he is a good skier.

I've enclosed my 2 critiques on our attendance. I don't think I insulted anyone if so it was not my intent but I did try to summarize what I did and didn't get out of it

SVF is out sick all week here so I sent you a ~~blind~~ blind copy of my version

Hope the hot desert finds you busy again so no idle thoughts can get in the way. I'm busy in 4 directions!

I'm sending a copy of MDM's latest doctrine paper which I got from U. of W/O because I know you like these things

Thanks again for a great time — Take care

Chuck

ASARCO INCORPORATED
Denver Colorado
March 9, 1977

To: S. Von Fay

From: C.E. Beverly

Critique on Lucian Platt's
Thrust Faults-Gravity Sliding
USGS Structure Seminar

Mr. J.D. Sell and I attended Mr. Lucian Platt's lecture on Thrust Faults-Gravity Sliding and Crustal Flexures on March 4, 1977. Mr. Platt gave a very lucid and pleasant historical review of thrust faulting, its initial recognition in the Alps over two hundred years ago and its present day proponents and their ideas on current theories of formation and movement.

The attached list of references suggests that Mr. Platt has thoroughly studied all theories of thrust fault development. His illustrations and slides revealed that he had toured Europe to study the Apennines and Alps and their tremendously long thrust movements.

He used the glacial rebound theories of Jacobs and LaFountain to explain his approach to a viable mechanism by Elliot--mainly gravity push. The process begins with a flexure in the earth's crust which could be caused by isostasy on an elastic plate. The weight of the advancing plate causes a slight bulge or flexure in front. Sediments shed from the thrust plate are caught in a moat between the flexure and the advancing plate. The moat builds ahead of and at a faster rate than the plate development. The pile of thrust plates depresses the entire area but the pile builds higher up than the crust is depressed down. It is still quite speculative as to how the initial plate gets on top, but there is evidence especially in the Grandfather Mountain Window area that the pile builds from the back to the front. As was pointed out in the questioning at the end, there are many field-related problem areas in Montana-Wyoming-Idaho in the thrust belt trying to find evidence of thrust sheet origin to the west. The possibility was raised that perhaps a westward moving plate initiated the thrusting. Obviously, the talk was geared to a scale that only true thrusters could appreciate. There was no mention of relating thrusting to any economic significance.

C.E. Beverly
C.E. Beverly

cc:JDSell
CEB:slr

ASARCO INCORPORATED
Denver Colorado
March 9, 1977

TO: S. Von Fay

FROM: C.E. Beverly

Critique on the 1977
Landsat Image Exercise
Salt Lake City, Utah

Mr. G. Bryan Bailey specifically requested a copy of this memo be sent to him.

A meeting was held at the ASARCO-Salt Lake City office March 4-7 to discuss the usefulness (pros and cons) of enlarged (1:250,000 scale) Landsat Imagery within a selected area of our district. The group convened consisted of John Collins as moderator, G. Bryan Bailey-Salt Lake, Jim Sell--Tucson, Jerry Biery--Knoxville, Larry Applegate--Spokane/Alaska, Del Olsen and Don MacIntyre--Vancouver and Chuck Beverly--Denver,

Everyone had plotted the visible structural elements for at least one enlarged Landsat image on a mylar overlay as per Mr. Richard Brown's instructions of January 5, 1977. The exercise in Salt Lake consisted of Messrs. Collins and Bailey projecting to scale, 2" by 2" slides of a particular Landsat image on paper on the wall for each of the participants' areas. This was done one at a time and everyone except the author of that particular projected image then proceeded to draw in the various linear and curvilinear structural elements. This took approximately 20-30 minutes in each case and was conducted at three different distances (approximately 20', 10' and 5') in order to see mega versus minor structure. When this unbiased group had finished then the author of the image would post his effort plus known geology next to the group's and explain what he had done and compare his work with the group's.

This type of approach to begin the meeting was very beneficial to getting everyone involved from the start and recognizing the significance of using distance when interpreting. Mr. Collins should be commended for initiating that format. The exercise illustrated that in a short period of time using the relatively inexpensive 2" by 2" slides anyone (even those totally unfamiliar

with the geology of an area, perhaps even a high school class) could plot nearly all the significant linears and curvilinears for an area. It also proved that if an area has had a geologic history of structural complexity, anyone could discover that fact in a short period of time. Usually such areas contained the ore deposits for that particular image. This exercise also proved that literally hundreds of linears or circles could be drawn which clutter the true picture for an area. So some arbitrary cutoff to detailed plotting must be exercised. In addition line weight or strength should represent the magnitude of the structure represented. Thus the Rio Grande Rift would receive a heavy line versus a light line or different colored line for small local faults. However, it should be emphasized that problems develop with Landsat Images where ore deposits are older than more recent superimposed structure or recent volcanism, younger rocks or gravels have covered most of the region as is the case in Arizona, Nevada and parts of Colorado and Kentucky. The significance of linears or circles related to ore in portions of these states is at best questionable, because one cannot indiscriminately project linears through valley fill or mountain ranges and reap a meaningful result. Similarly, problems develop with utilizing Landsat when dealing with stratabound deposits such as the Sullivan or Carlin Mines. Because of the significance of structure to ore in most areas, it was argued in Arizona and elsewhere that if the individual field checked (in approximately 3 months time) all the structurally complex areas on each image at least one orebody would be found. The point is well taken and in early historical times this could be done but not in 1977.

What follows is a capsule summary of each participant's comments of his own work and its significance to finding ore:

> Larry Applegate: Little geology is available for the area in southeast Alaska. A plot of 1st through 5th order structure revealed many complex areas. 90% of all the known mines in the area lie within one circular feature of extreme structural complexity. Based on one day's effort the structural fabric of a region was produced which was not known previously.
>
> Jerry Biery: A very subtle topography contrast exists along lithologic contacts. Major ore concentrations are aligned along N-S lineaments. Major lineaments that control the position of the Cumberland River also control ore deposition. Surface expression of ore is minimal where it occurs it outcrops as mineralized breccia. Two or more erosion surfaces are present and rejuvenated lineaments exist since the formation of the Knox dolomite which hosts ore. In his opinion, other geologic evidence guided them into areas to drill but they coincide with lineament intersections.

Chuck Beverly: Regional geologic mapping exists for the entire area. Landsat exhibits local structure quite well and all caldera structures are easy to distinguish in the San Juan Volcanic field. The image exhibits several circular features which may be yet unmapped calderas. Band 5 exhibits a better tonal contrast than Band 7 for some ash-flow tuff units. Band 7 is better overall, however for structure. Known alteration zones are difficult to find on the image and the actual relationship of presently exhibited structure to known mines is not well expressed. Alteration and mineralization from published mapping usually guides us into an area initially. Rock types can be separated only in a gross sense on the image. They are useful for an initial review of regional structure.

Jim Sell: Landsat cannot locate ore forming phenomena in Arizona due to destruction of spectral characteristics of rocks due to alteration. No set of linears can be demonstrated to locate drill targets because no set of linear intersections relates to presently known ore deposits... possibly due to younger cover rocks and younger structural overprint? ?

George Stathis' Image/by J.D. Sell: No linears.

Don MacIntyre: There appears to be good correlation of the government's mapping of geology with the Landsat Image based on slight tonal differences, lack of lakes or vegetation in the Yellow Knife area. The vein mineralization is related to a shear system parallel to greenstone facies rocks. General good correlation of Archean vs. Proterozoic rocks and structure exists. On the basis of tonal contrast the correlation is best in areas of no previous mapping.

Del Olsen: In the Rocky Mountain Trench region of the Sullivan Mine, there is no correlation of Landsat to rock types, or even major structures. One cannot pinpoint boundaries of igneous-sedimentary units.

Bryan Bailey: In Nevada at 1:1,000,000 no major linears can be attached to known ore. At 1:250,000 areas of alluvial cover were eliminated and outcrops reveal that detailed structure and most importantly NW-NE intersections are significant and related to mineral deposit location. A superimposed plot of mineral deposits and structure revealed no outstanding correlation, but several were aligned along one structure.

In summary, it was learned that Landsat Images at 1:250,000 can provide a useful initial pass or review of the structure for a region in a relatively short period of time. The images projected on a wall appear to be easier to

see which is a plus for ordering both slides as well as 1:250,000 scale images since those would be needed for actual field work. Initially, rotation of the image is important in any interpretation in order to see all the structure. The most structurally complex areas usually contain the most mineralization with some exceptions. Ore deposits are usually found in structurally active areas where reactivation has occurred repeatedly since the Precambrian expecially in Laramide-mid-Tertiary time. Linear and curvilinears of 1st, 2nd and 3rd order are usually most important. Everyone agrees for an initial pass into an area, Landsat Imagery at 1:250,000 scale can be useful and its price roughly $20/image is not prohibitive.

The meeting lacked concise discussion on the direct useful relationship of Landsat to known regional ore deposits or their related characteristics. We were promised better data would be available in the future since some of the government Imagery from the center at Sioux Falls are admittedly quite poor. It was pointed out that some of the literature circulated to date was not useful because it did not pertain to geology related applications of Landsat.

The question was asked: Where is this program headed from here? Apparently ASARCO money is already budgeted according to Messrs. Bailey and Collins to experiment with enhanced imagery under a budget labeled from Cal Moss. With approval of our supervisors we were told by Messrs. Bailey and Collins at least one image per district would be enhanced by a consultant named Dr. Goetz of Geo-Images Inc. at a total cost of approximately $3,000/image. The attached circular describes Geo-Images services. I recommend that image 36-34 (the Summitville, Colorado area) be used for this office since Denver office geologists have spent the most time in that region and are familiar with the geology and it is an ongoing project. Only briefly and vaguely was Dr. Goetz's service discussed. Apparently we would get all of package #1 plus a high pass filter image which exhibits structure. It seems to me however that because of the spectral bands used, alteration and rock types would be more readily visible. This could be of use in locating caldera-related ore. Mr. Bailey briefly discussed the Geosat Committee and Mr. Brown's role in it was emphasized.

The meeting ended on a friendly note but with no real summing up of what had been discussed or much detailed discussion on how to interpret the enhanced images when and if they arrive. Mr. Bailey asked us to send him a summary of our thoughts with your approval to order an enhanced image. We were assured money for the enhancement would not come out of your budget. Mr. Collins listed tentative orders for the enhanced images.

C.E. Beverly

C.E. Beverly

BLIND CC: JDS

Landsat

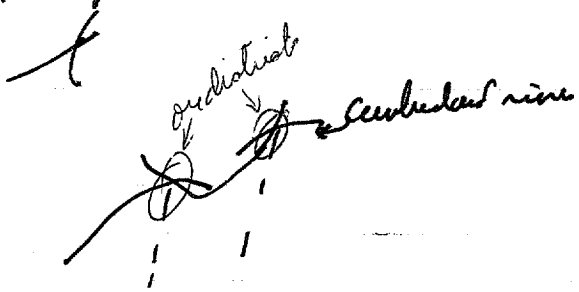
Sat. March 5, 1977.

Jerry Berry - Knoxville Biery
DH Ollie Olson - Vancouver
DW Don McIntyre - Vancouver
Larry Applgot - Spokane
Chuck Beverly - Denver
Jim Fell - Tucson
Brian Bayley - SLC C. BRIAN BAYLEY
John Collins - Convenor.

1. General review & Thoughts by group on each photo
2. Followed by discussion by primary author.
3. Total review.

SE Alaska - Larry Applgot
Intersection of linears, w/ converging, + large & smaller, nested, circular patterns, strongly reinforces areas to be checked when known to contain some metallization.

Tennessee - Berry.
Large features ± regional structure & stratigraphy.
100 mill 5-6% Zn on N and / Rockgate Knoxville / Cumberland river. (Elmwood).
NE linears & N-S linear intersection very good on district - mine zone
district ↑ ↑ radio mine
may be in part curved intersection Peachgrove or Beachgrove (SV?)



Landsat - Saturday (Continued).

San Juans - Beverly.

Far away basis looks continues to show a point out closer detail analysis. Indicating continued structural control or activity over period of time. Detailed analysis may, & does indicate older structure, partially, & continually reactivated which may as at Platoro-Summitville be a real guide to mineralized intrusion zones.

Phoenix-Tucson - Sell

Numerous lineas in valley & x-cutting ranges plus circle of various sizes were outlined in rapid fashion (as in previous descussion). DJC suggested additional work in SE area, & Sil Bell area. Discussion period also suggested They would have a near impossible task to confirm or suggest some lineas etc either by detailed analysis or ground truth. Bailey et al suggested that if this had been done & all circle-linear intersects checked then a number of deposit would have been in the near vicinity. It was then stated that a broad survey by helicopter could do that in a relatively short time but was also stated that no new ones have been found by a direct clue such as SB & The Miami dist have. The subtle clue as S Manuel (not on a intersect) & Lakeshore (near a valley linear) or Vekol (not on any line of importance) would have been found without Ground Truth checking and large geol. thought-concepts implemented.

Alteration discrimination is still down the road a reduction effector.

J W Sell

Salt Lake Hilton

Reprints of:

Goetz, A. F. H., et al., 1973, Application of ERTS to Geologic Problems on the Colorado Plateau Arizona, Proc. of 3rd ERTS Symposium, Dec. 10-14, Washington D.C.

Goetz, AFH, 1973, Quality & Use of ERTS Information on Geologic Applications. Proc. of the 4th Annual Conf. on Application of Remote Sensing of Arid Land Resources & Environment, Nov. 14-16, Tucson, Az.

J W Sell

Salt Lake Hilton

continued

Blackstone, W.L. Jr., 1973. Geology of photolineaments, Great Divide Basin, Wyoming. NASA Tech. Report NASA-CR-133634, 14p.

J W Sell

Salt Lake Hilton

continued

Morrison, R.B. & McCooley 1973, Application of ERTS-1 Multispectral Imaging to Monitoring the Present Episode of Accelerated Erosion in Southern Arizona. Proc. of the Symp. on Significant Results Obtained from ERTS-1, NASA SP 327, p. 283.

Rowan, L.C. & others. 1973, Mapping of Hydrothermal alteration zones & regional rock types using computer-enhanced ERTS MSS images. 3rd ERTS Symposium Dec. 10-14, 1973, Washington DC.

Landsat - Sunday

Yellowknife - MacKenzie.
Successfully separated Archean vs Paleozoic. Greenstone belt to east outlined but western missed. Several trend areas, 2 structure etc, are old burns.
Bedding shears + x-cutting shears in greenstone is best for Yellowknife gold deposit.

SE BC - Olsen.
Sullivan area in zone of NS + EW with Rocky Mtn Trench nearby. Several lineaments throughout.

Nevada - Bailey.
Outlined Qal-BR w/ moderate success plus mining districts. Thinks we should work by stages + gain more output of district (known) control. Our shotgun going to approach had much trash but most intense 3 zones contained the 3 main trend of mineral districts.

NW

Geological Remote Sensing from Space by F B Henderson III, + G.A. Swann, Editors
Report of the Ad Hoc Geological Committee on Remote Sensing from Space
with Recommendations for a Geosat Program.
Flagstaff, Az May 10-14, 1976
Compliment of The Geosat Committee Inc
690 Market Street
SF CA 94104

See passout sheet.

ASARCO

Southwestern Exploration Division

February 22, 1977

F. T. G.
FEB 28 1977

TO: F. T. Graybeal

FROM: J. D. Sell

ERTS Exercise
Phoenix-Tucson Area

For the ERTS/Landsat study, Mr. Bryan Bailey supplied two enlargements of the Phoenix-Tucson area (Nasa Erts E-2099-17213 photo); one in black and white, the other a color composite of bands 4, 5, and 7. After studying both photos I chose the color composite for detailed analysis as it appeared to have better resolution, clarity, and tonal change characteristics. The photo covered from north of the Globe-Miami mining district to south of the Silver Bell district. The west boundary was beyond the Sacaton area and the east boundary beyond San Manuel.

Significant surface disturbance in mining areas, especially with large waste dumps and tailings ponds, is readily visible and is outlined on the clear mylar overlay in red. Less significant are the block cave hole at San Manuel and the work at Lakeshore. Unnoticed, except as a rectangular outline, is the Sacaton pit area. A similar rectangular area east of the road north from Casa Grande is a cleared, uncultivated field. No tonal clue could be seen for Poston Butte, Blackwater, and Vekol Hills mineral deposits.

The large area of road system (3 x 3 miles) north of Mesa is readily visible as is the site of a heavy equipment testing facility. However, a road mileage test center south of Tempe on the east end of South Phoenix Mountain and the center in the San Tan Mountains are not noticeable.

No incident of linears appears to outline the known mineral districts.

Of interest in the SW quarter of the photo is Big Foot ? in area 1, an uplifted conglomerate block. Note also the limonitic, pyritic yellow tone to the surrounding area. At area 1 the limonitic tone is weathered Precambrian granite cut by a few Laramide dikes and masses, generally unaltered. Going to the southwest are a number of tonal and shape areas characteristic of Big Foot and in the vicinity is the limonitic color tone. It would appear that areas 2, 3, and 4 should be checked for possible porphyry occurrences.

A similar color tone, slightly reddish, lies NE of the Silver Bell area (5) and continues north of the Ragged Top fault into area 6. Areas 7, 8, and 9 are similar to the Silver Bell 6 coloration.

Coloration zones are not visible around the porphyry deposits of the Globe-Miami, Ray, Christmas, and San Manuel areas.

James D. Sell

James D. Sell

JDS:lb

cc: GJStathis

JDS → GJS → FTG
(see page 3)

ASARCO

Southwestern Exploration Division

February 10, 1977

F. T. G.
FEB 15 1977

TO: F. T. Graybeal

FROM: G. J. Stathis

ERTS/LANDSAT photo exercise of the Tucson-Wilcox-Cananea region and of the "Walker Lane" (Walker Lake-Yerington-Virginia City) Region

Introduction

For the Tucson-Wilcox-Cananea exercise a 39" square enlargement of the Band 5 black and white enlargement of photo E-2458-17104 taken on April 24, 1976 was used. A 39" square false color enlargement of photo E-2134-1716 which covers part of the area of the b&w enlargement was supplied but not used in the exercise because it would not overlay the b&w enlargement.

For the "Walker Lane", Nevada exercise, both Bands 5 and 7 b&w 39" square enlargements of photo E-5495-17141 taken on August 26, 1976 were used. A 39" square enlargement of the false color composite of photo E-5495-17141 was supplied by Bryan Bailey but was not used due primarily to time limit. The Band 5 enlargement was examined first and an overlay was constructed. Subsequently, the Band 7 b&w enlargement was examined and an overlay was constructed. It became apparent that the Band 7 enlargement showed somewhat more detail than the Band 5 enlargement.

The photographs were examined intermittently from 2 to 4 hours over a 6 day period. This time spent includes preparation of a second "geographic" overlay for both the Tucson-Wilcox-Cananea and "Walker Lane" photos. This "geographic" overlay shows location of mountain ranges, valleys, towns, important mining districts, major prospects, lakes, partial tracings of rivers and highways, and hot springs ("Walker Lane" photo only).

Contrary to the instructions given in your memo of December 27, 1976, the entire photo area was examined rather than specific, less disturbed, altered mineralized-mineralized zones. This was done because: 1. scale of the photos are such that areas encompassing specific altered-mineralized zones are quite small; 2. rather poor resolution of the ERTS/LANDSAT enlargements, perhaps caused by use of second, third, or fourth generation negatives by the EROS lab. Approximately 80 percent of my time was spent in examining the "Walker Lane" photo because of a much greater familiarity of the regional geology.

"Walker Lane" Exercise -- conclusions

1. The Basin & Range faults, the main structural feature of this region, show up very well on the photos as they do on any conventional, fixed wing, air photograph that I have seen of this region.

2. The northwest "Walker Lane" discontinuity which separates the north-trending mountain ranges on the north from the northwest-trending mountain ranges to the south shows up well. This line of discontinuity can be traced on standard 1:250,000 scale AMS topographic sheets just as well.

3. No widespread northwest-trending, shear or fracture system parallel to the Walker Lane zone of postulated, major right lateral, strike slip movement was discerned in the photographs.

⊗ 4. Faults such as the Comstock and Silver City faults and several important ones in the Yerington region; e.g., Blue Jay, Gallagher Pass, Mickey Pass are not discernable in the satellite photographs. Yet these are significant, in the exploration sense, faults in these mining districts. The problem again is one of scale and resolution.

5. There appears to be no discernable structure(s) accounting for the location of individual mining districts.

6. The ERTS/LANDSAT photos are especially good in showing circular features see p 3 such as the Soda Lake Maar just west of Fallon and the recently recognized Little Walker Caldera just northwest of Bridgeport, California. In addition, a few unexplained circular features were noted at the southwest corner of the photo which covers the Sierra Nevada Range.

7. Also, there is an indication that Basin & Range-like structures see p.3 partially extend into the Sierras. Similar phenomenon has been noted south of the photo in the Bishop-Mt. Whitney-Lone Pine, California region.

8. Northeast-trending linear features are more sharply defined on the Band see p.3 7 than the Band 5 photo. These linears occur both north and south of the "Walker Lane" and appear to counter the trend of Basin & Range faults. The significance of these linear features is unknown. There are, no doubt, more of them than I have shown. The problem is that Band 7 photography appears to have more contrast resulting in accentuation of sun shadows in canyons, ravines, etc. Thus, it is hard to assess true linears from apparent? linears caused by low-angle sun shadows in northeast-trending canyons.

Tucson-Wilcox-Cananea Exercise -- conclusions

1. Lack of any recognizable structures in the Pima mining district south of Tucson, at Cananea (Sonora, Mexico), or Sunnyside (Patagonia Mtns.).

2. Arcuate features noted in the Santa Catalina Mtns. Their significance is unknown.

Conclusion

A study of ERTS/LANDSAT photographs has led to the conclusion that these photographs are not particularly useful in exploring for mineral deposits

in the Basin & Range province of the western United States. The current state-of-the-art is such that scale and resolution of these photographs does not permit the recognition and recording of geologic detail that is permitted by available conventional air photography and including U2 and Skylab photography.

George

G. J. Stathis

GJS:lb

cc: JDSell

(1) Do linear grooves in the photograph interfere with interpretation. Is this why circular features show up more clearly?

(2) By chance the mining districts in Nev. can be related to NE structures extending out of the Sierra Nevada.

(3) With reference to sun angle problems in #8 is it possible that "apparent lineaus" which are an artifact of sun angle and are thus topographic may represent actual structural patterns and that further work with photos at different angles (time of day) might be useful?? Morning sun would accentuate NE structures, afternoon sun accentuate NW structures.

2-16-77

To: FTG

1. No linear grooves do not interfere with interpretation. As a matter of fact. These grooves are significantly more "enhanced" on band 7 than band 5 photographs. They are somewhat annoying though. No I wouldn't say the presence of these linear grove features cause circular structure to stand out more clearly.

2. I really cannot see these NE structures in the Sierras

3. Yes I think many of these topog. lineaments due represent bona fide structural zones of weakness (shallow). Yes, photos at different times of day & season should be a very interesting exercise — A Good Idea Fred!

GJS

L. D. James.

THE APPLICATION OF MULTISPECTRAL SCANNING SYSTEMS TO GEOLOGY

by

Dr. J. W. Norman
Imperial College, London

With supplementary information on
Geological Sedimentation by

Dr. D. Bannert
Hanover, West Germany

ERTS Earth Resources Survey Study Report, C. Multispectral Scanning Systems and Their Potential Applications to Earth Resources Surveys, Data Applications, pp.C3-1C3.

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1. INTRODUCTION

Line-scan devices recording in the far infrared are already bringing new information and ideas to geologists. Whilst the present state of the art of recording and interpreting line scan multi-spectral imagery does not yet approach the capability of multi-spectral and multilayer photography* at similar wavelengths, there are exciting implications in the long-term developments that will increase the amount of detailed information available to the interpreter to such an extent that he may look to this method in preference to air photographs though perhaps retaining photography to analyse the relief. Much of the information available for forming this opinion derives from laboratory and multi-band spectral photographic studies, but there have been sufficient field studies in line-scan sensing to show that the possibilities of this technique are not merely academic, but also of practical significance.

In most operations the geologist's prime equipment is a geological map. This in general shows the areal distribution of different rocks and soils, their structural relationships, and geometrical data which enables inferences to be made about sub-surface phenomena. The preparation of this basic geological map is the initial goal of many types of investigation, and subsequently forms the basis of many later specialist operations. Commonly a basic geological map will be prepared by government agencies, and this later may be exploited by oil and mining companies who will be able to discern which areas are likely to be barren from their point of view, and which are the most promising. Engineering geologists may be able to make inferences about sub-surface drainage, run-off characteristics and sources of materials etc. Hydro-geologists will be able to infer structures that might be water bearing etc.

The obvious geological role for MSS is this early reconnaissance stage, when it will produce data for the basic map, and in a number of instances, special data for other purposes.

Apart from the relatively early appearance of the scanner at Michigan University, much of the practical use of scanning devices reported in the geological literature concerns instruments confined to non-photographic infrared wavelengths. In view of the much smaller volume of information on scanning devices in the visible and ultra-violet part of the spectrum, occasional reference is made to multi-spectral photography, or even multi-band photography from which are drawn conclusions about likely results using a scanner in analogous situations.

* *Multilayer photography ≡ photography using colour or false-colour film.*
Multispectral photography ≡ photography using multiple cameras, colour filters and black and white film.

2. PHYSICAL CHARACTERISTICS

Most geologists are primarily concerned with rocks. These may be uniform in composition, or be formed of a range of different minerals with different crystal sizes. The crystals may be randomly oriented or show a strong parallelism.

In the greater part of Europe rocks are in various stages of disintegration at the upper surface, and are covered by soils which may be formed of residual material derived from the broken down rock, possibly with some characteristic minerals removed by water or wind; or they may have been transported to their present position by water, gravity, ice movement, or wind, in which case these transported soils may be derived from completely different rocks many kilometres away. The soils are usually porous but may be permeable or impermeable to water. They may be dry or damp and have surface or subsurface flowing water that may be acid or alkaline. In some hot climates upward leaching from bedrock with near surface evaporation may form a layer of very hard material (e.g. calcrete or laterite) in soil almost at the surface, and roughly parallel to it, but perhaps discordant to the bedrock.

On top of the soils in Europe it is normal to find a layer of vegetation which often indicates soil properties, but also varies with other parameters such as latitude, amount and seasonal distribution of rainfall, orientation of slopes to the sun and prevailing winds and ground drainage. In large areas of Europe the natural vegetation has been interfered with by man, or replaced by crops. But in a wider, global context, there are vast areas where the natural vegetation has been undisturbed long enough to form plant communities significantly related to the geological environment, and thus provide useful interpretation data for photogeologists.

The area of exposed rock will in general be found to increase with altitude, and bands may be detected around coasts and cliffs or in deeply incised river valleys. Deserts, both hot and cold, are places where bare rock and dry residual soils may give MSS responses more directly related to the rock type.

Some rocks are layered, for instance those which were lain down in water, while others may have been formed from a molten mass that cooled at a rate permitting sequential crystallisation of different minerals.

Some rocks are polished by blown sand or ice movement and are usually gently rounded rather than being planar over large areas.

Usually the exposure of rock allows the commencement of physical and chemical processes that change the surface. The degree and type of change is related to the rock's properties, but also to time.

Thus a new lava flow may be relatively smooth on the surface compared with one several thousand years old in the same vicinity, and show differently on imagery. Several centimetres below the surface the rocks may be identical in every respect, although the age difference may be of importance to a geologist.

Details of rock spectra are being recorded (Ref.1), however from what has been described of field conditions, it will be seen that laboratory measurements of the properties of clean rock surfaces or powders will not be a sound indication of the MSS response from an aircraft or satellite, and spectral signatures obtained in the field may also only be relevant in a small area. It has been shown that both moisture and lichen can affect the reflectance of 'bare rock' (Ref. 2) and the effect of moisture on soil reflectance has been exploited extensively by photogeologists, although experiments (Ref. 3) show these to be quantitatively unreliable.

There are also time effects to consider. The relative infrared emission of two adjacent materials can reverse during the course of twenty-four hours (Ref. 4).

3. DISCIPLINE REQUIREMENTS

In the context of an airborne imaging technique, geologists would like means of mapping the distribution of surface materials and their characteristics with sufficient additional data for extrapolations below the surface. This means aquiring three-dimensional data on the inclination of rock layers intersecting the ground surface so that extrapolations can be made of subsurface geometry and relationships. It is essential to distinguish between slopes of purely soil material and those due to rocks near or intersecting the surface. The direction of the inclination and the amount need to be recorded, although for reconnaissance mapping the amount of inclination need be only a semi-quantitative estimate. Photogeologists on such work classify inclinations as: vertical, steep, moderate, low and horizontal. Stereoscopic 'vertical' images are desirable for this work as the interpreted information is more easily converted to map form, and more amenable to quantitative geometrical analysis. Oblique views can of course produce useful information in steeply incised terrain that would be difficult to sense adequately from above.

Variation in rock and soil properties, their history and response to erosion all combine to form a complex pattern of shapes at the land surface. Using analogies, photogeologists exploit these landforms to interpret underlying rock type and structure (i.e. the geometrical relationships with adjacent rocks). Thus thickly layered tilted rock systems may form a pattern of long parallel ridges, perhaps steeper on one side. A linear interruption and displacement might be a fault; a roughly circular interruption might be an intrusive body such as a salt dome, granite cupola or volcano.

Brittle failure causes the widespread occurrence of fractures termed 'joints' if there is little relative movement of the sides, and 'faults' if there is movement.

Faults and fracture systems are also a valuable source of geological data. They can be used to assess regional stress patterns and sense the position of intrusive bodies, or features concealed by sediments. They show in a variety of forms, usually as rectilinear or gently curvilinear lines representing the intersection of the failure surface with the land surfaces. This line may be a gap or depression of a few centimetres to a few metres wide. It can be the site of an abrupt vertical change in relief or a horizontal displacement varying from centimetres to kilometres. It may only show as a damp line of soil. All faults with movement are important to geologists, but for fracture trace analysis a useful minimum size would be a fracture trace of as little as 0.5 cm width tapering out along its length, which in turn might be 100 m.

Lineaments are also of interest. These are long relatively straight natural disruptions of other landforms that are probably related to deeper crustal failures which may have become buried by later post-failure rock formations.

It is desirable to have unique signatures of groups of rocks, so that if one group dips below the ground surface and can be correlated with another group emerging elsewhere, informed speculation can be made of subsurface configurations. But this signature can take forms other than a sample rock spectral signature and may be such features as a unique plant assembly or distribution, a peculiar form of weathering, a contrasting resistance to erosion compared to adjacent rocks, unique permeability characteristics etc. One series in central Africa, is distinguished by being liked by termites; air photographs show the distribution of their mounds, thus showing the underlying rock unit! It is more usual at present for photogeologists to map units of rock without being able to ascertain their identity; but if 'Rock A', 'Rock B' and 'Rock C' can all be interpreted before a field visit, then sampling can be planned to ensure adequate check identifications.

To be able to detect rock and soil boundaries is a major advantage, even if the imagery does not go so far as to present sufficient data to enable the units to be named. The same might be said of determining the position of faults.

The identification of materials and their boundaries is more important in the first instance than a true geometric presentation of results, provided the imagery contains sufficient data to recover their true positions by later processes. It is more important that boundaries should be known in relation to ground relief. A line of wet soil crossing a slope obliquely is usually more significant than one marking the bottom of a valley.

Periodic investigations are not usually called for in geology, with the exception of volcano monitoring (say in terms of several months). There is some point in sets of imagery at different seasons, for sometimes additional data is obtained at different stages of vegetal growth. Additional sets of imagery over an area may be called for when substantial instrumental advances are made.

An immediate availability on demand would be valuable for major disasters, such as floods and earthquates, when communications may be interrupted.

The minimum resolution required will depend on the nature of the project in hand, and it is difficult to generalize.

The area of ground that will be of interest is impossible to define. From an applied geological aspect, theoretically all dry land could be involved eventually. The younger sedimentary rocks are of interest to petroleum geologists; the older sediments, igneous and metamorphic rocks are of main interest for mineral prospecting. Engineering geologists become involved in small areas over all rock types.

The following suggested geological applications of M.S.S. involve various instrumental demands. Resolution is not required in terms of standard bar targets or modulation transfer functions, but as ground features to be recognised by the interpreter. There is a critical difference between an instrument being able to sense an object, and its ability to display an interpretable image (Ref.5). A possible indication of the resolution required is to consider that necessary to produce identifying data and boundaries of areas of 2 to 3 mm. square on maps at the scales listed in Table I. To produce these results it would normally be good practice to operate at a larger scale than the final map product. The scale must not be so small that critical features cannot be detected and outlined, or so large that when examined visually they cannot be seen and judged against their environmental setting.

NATURE OF STUDY	SCALE(S) OF MAPPING	AREAS INVOLVED	REMARKS
International aid projects	1:100,000	Perhaps hundreds, but usually thousands or tens of thousands of square kilometres.	Usually 'pump priming' projects of general mapping, but also studies for specific targets. Normally applies to countries outside Europe.
Routine government surveys of basic geology	1:50,000 1:25,000 1:10,000	Complete countries.	Usually a slow piecemeal operation over many decades. Edited reductions as regional maps may be produced at 1:100,000; 1:250,000 and 1:1,000,000 scale.
Petroleum prospecting	1:100,000 1:50,000	Hundreds or thousands of square kilometres.	Promising areas may be mapped at larger scales. Government maps may eliminate much regional mapping.
Mineral prospecting	1:50,000 1:25,000 1:10,000	Hundreds or tens of square kilometres.	Increasingly large scales are used for more promising areas.
Hydrogeology	1:100,000 to 1:5,000	May vary from a whole country to a few square miles.	
Engineering Geology	1:50,000 to 1:1,000	From a few hundred square meters to 100 square kilometres.	Projects are very varied - e.g. a road route of 100 km a bridge site of 0.5 km^2, dam site of 0.5 km^2, an aerodrome of 50 km^2.

TABLE I : Some broad generalizations of the scales and areas involved in photogeological studies.

4. APPLICATIONS

4.1 General Geology

A basic geological map is usually the foundation of all applied studies, and field relationships are usually involved at some stage. This requires a knowledge of the rock and soil types, and there are good indications that MSS can aid this work. For example, Lyon and Patterson (Ref. 6), found that they could discriminate the spectra of quartz-monzonite, andesitic and basaltic volcanic rocks and their soils in the Sonora Pass, California. Rowan and Cannon (Ref. 7) have described an investigation in which the thermal infrared results of an aircraft survey distinguished limestone, dolomite and granite in an arid area. This interesting ability to recognise two photographically similar rocks limestone and dolomite, is also borne out by work in the Arbuckle Mountains, Oklahoma, (Ref. 8). However, it was also shown that the imaging has to be done at night to be effective in detecting this type of contrast.

Studies in Yellowstone National Park (Ref. 9) showed that gravels can be distinguished from bedrock and till by a darker tone on evening infrared imagery in the 8-14 micron band. The dark-toned anomalies were found to be more diagnostic of deposits on high slopes and the plateau top than of deposits in valleys and basins. In summarising other work it was stated that thermal activity is the only geological data registered directly by thermal infrared imagery; other geological features showing indirectly, by their topographic expressions chiefly, include: fractures in bedrock, pressure ridges in lava, glacially moulded topography, river terraces, alluvial valley fills, talus slopes and alluvial fans.

In other studies conglomerates and clays showing in a road cut could be differentiated by the varying moisture content (Ref. 10), and outcropping sandstone could be traced where it extended under a thin overburden (Ref. 61).

A number of instances have also occurred in which photogeologists have seen subtle changes in photos of rocks such as granite, that cannot be sensed by a geologist on foot. There may be even more scope to detect such changes when scanning at a number of wavelengths.

In a study of multi-spectral soil mapping using computer analysis of spectral signatures (Ref. 11) six categories of soils could be mapped from aircraft levels. It was considered that there were possibilities of more detailed mapping according to the user requirements, providing that adequate ground control data was acquired at the time of scanning. Areas of vegetation were not included in the study but it was stated that there were variations in the vegetation correlating with soil which gave promise of the technique being extendable into such areas.

Wolfe (Ref. 12) found that best distinction was achieved between materials of different specific gravities when on a pre-dawn infrared survey. (The specific gravity is of course, directly related to the thermal inertia).

The foregoing examples are taken from aircraft studies, but there are examples of Gemini and Apollo photography displaying geological information. An example (Ref. 13) showed that photography from Gemini IV could be useful for small-scale mapping purposes when used under optimum conditions, but with standard interpretation techniques, identification on conventional aerial photographs could still be made with a higher degree of confidence.

Preliminary examination of ERTS-1 M.S.S. imagery also shows that at least some major regional geological features show clearly.

Small scale imagery is almost certainly going to add to the information of regional and continental sized problems, such as plate tectonics, which are at present slowly yielding to the ground piecemeal approach. This has already been shown by the use of photography. One test (Ref. 14) has exploited Apollo 9 photographs over parts of Ethiopia for updating geological knowledge in remote areas, and the results have led to a new hypothesis of crustal block drifting in these regions. Such work requires imagery of very large areas at small scales, so that the effects of slowly impacting continental sized crustal blocks can be seen on the grand scale. For this type of work it should be possible to recognise relief features several hundred metres across, and few tens of metres high.

The view from above obtained by aircraft and satellite tends to make fault and major joints more obvious than from the ground in soil covered areas. This aids fracture trace analysis in which the patterns and relationships of fractures are exploited to help solve bedrock geology.

Scanning data should prove useful in the study of sediments and sedimentation. Detailed investigations will mostly deal with sea bottom structures and offshore springs in selected areas; small scale investigations will deal with current patterns and sediment transport by water. Observations of smooth water within visible wavelengths will give most information on these aspects. Thermal infra-red bands give information on temperature distribution caused by offshore springs and sediment load. Sediment transport by currents can be traced on infra-red imagery if the current temperature is different from the surrounding water, but only the temperature distribution at the surface is registered. Bands in the visible part of the spectrum provide deeper penetration into the water, depending on sediment load and daylight influence in the water.

MSS should be useful for collaborative studies with geochemists and geophysicists. For example, it could show the origin of soils, helping geochemists to understand varying background analysis; it could be used to check ambiguous geophysical anomalies, such as to show whether changing electrical properties are related to ground moisture or other causes. The wide ground coverage of scanners is sometimes used in low flying geophysical aircraft instead of the conventional small image camera used for recording track paths. The wider strip of ground imaged makes it easier to identify the actual route taken, and being able to image the route at night makes it possible to work at night in some areas where the daytime turbulence is objectionable.

4.2 Petroleum Geology

Petroleum geologists are extensive users of photogeology in the search for suitable sedimentary source rocks for oil, and structural and stratigraphic traps. In the long term, MSS may help detect lateral changes in rock strata (facies changes) that will indicate potential stratigraphic traps. Structural traps can frequently be determined by routine basic geological interpretation techniques.

Lintz (Ref. 15) in reviewing 'remote sensing for petroleum' comes to the conclusion that the sensing from E.R.T.S. is not likely to result in the detection of new surface structures, except in inaccessible and inadequately known regions. The advantage of the spacecraft missions for petroleum exploration is more likely to be the synoptic views of entire sedimentary basins in which may be seen for the first time lineations not visible from large-scale data. The interpretation and understanding of these prospective new lineations may in turn lead to new concepts in structural control of petroleum traps. The space data may therefore lead to the identification of localised areas where more detailed remote sensing with aircraft will be applied.

4.3 Mineral Exploration

Prospecting for minerals is a much more complex procedure than for petroleum. There are many types of minerals, and each can occur in a variety of settings, and may suffer alteration after emplacement.

Mineral deposits consisting of metal sulphides near the ground surface are well known to have zones of oxidation that generate heat. It has been suggested (Ref. 16) that there ought to be a possible temperature rise of 0.1 to 0.3^{o}F. above the ambient temperature at the surface in the vicinity of such ore bodies. Whilst this is within the bounds of detection under ideal circumstances with available equipment, it is extremely small in relation to the diurnal temperature range and as yet there does not appear to be any successful exploitation of this phenomena reported. This oxidation thermal anomaly could only be detected "at some distance below the surface where there is isolation from ambient meteorological conditions" (Ref. 17).

Attempts made to get imagery representative of sub-surface thermal anomalies in a desert terrain (Ref. 18) were disappointing as no unambiguous correlation could be made. It seemed that variations in surface materials may have had a masking effect in the desert environment. Surface salt intrusives showed clearly and it was considered that the infrared imagery might be useful for the detection of hitherto unknown surface salt plugs with little or no topographic expression.

However, in a study of coalmining areas (Ref. 19) it was claimed that "acid producing areas are detectably warmer than non-acid producing areas. It may now be possible to map the acid producing areas in other regions of Appalachia". If this can be done for the relatively small amount of oxidising pyrite in coal seams, then the possibility of detecting metal sulphide ore bodies is still of possible interest.

An interesting application in oxidation zones is the study of iron absorption bands in the near infrared and the mapping of iron-rich soil and rocks. Commonly, metal deposits often carry a proportion of iron in the form of oxides and sulphides, and although the more economically valuable minerals may have disappeared due to weathering, oxidation, and leaching at the surface, there is frequently a residual deposit of iron-rich minerals left (- the 'Gossan' of the Cornish miner or 'Eisenhut' of the German). The detection of such areas with a high concentration of limonite or haematite is frequently a significant pointer in mineral prospecting, for unaltered ore may still exist below the surface.

The exploitation of spectral signatures in desert environments is an interesting possibility although it is reported (Ref. 20) that the number of minerals with usable absorption/reflection features in the 3- to 5-micron region is limited, but includes such common industrial minerals as silica, limestone (and other carbonates), gypsum, phosphates, and evaporites. Silica deposits (both diatomite and pure silica sands) have been detected by this method. Field tests of carbonate rocks and gypsum appear promising.

It has been reported (Ref. 21) that "it is possible to map rapidly and in detail, from low aircraft altitudes, a large outcrop (like an open pit of a mine) and to delineate the areal distribution of the mineral assemblages or alteration zones in the ore".

However, it seems likely that most of the surfaces orebodies have been discovered, and the search is now for concealed orebodies. Basic geological mapping is of use in this respect to isolate areas of promise, and to reduce the time wasted in detailed studies of areas in which the rocks are likely to be barren. One indirect method is to exploit mineral influences on plants that have roots sampling below the ground surface. It has been shown (Ref. 22) by a controlled laboratory experiment that the spectral reflectance from bean leaves varies fairly

consistently with the amount of lead or zinc in the soil when other factors are kept unchanged. Further current experiments show that this effect can be found with other economic metallic minerals. From this it may be inferred that there is a possibility of a multi-spectral sensing programme being used to detect the influences of metals on, say, one species of tree growing in an area where there is possible mineralization concealed under the soil.

Field tests have shown that soil in areas of mineralization can directly affect the colour of red spruce and balsam fir in both the visible and near infrared spectral regions (Ref. 23). Similarly a correlation between the infrared spectra and copper in soil and foliage of Pinus ponderosa growing in a copper-rich area was found, although there was no correlation in the laboratory measurements (Ref. 24).

Some intrusive orebodies create a zone of alteration in surrounding rocks that may be amenable to detection when viewed on vertical imagery.

In a test of the use of air infrared surveys for detecting coal-mine fires (Ref. 25) it was concluded that shallow fires (less than ten metres from the surface) were easily detected, but at intermediate depths (from ten to thirty metres) the fires were detected when heat was carried to the surface by convection in open cracks, or if the fire had been burning for the several years necessary to permit heat to reach the surface by conduction. At depths greater than thirty metres fires were only detected if convection was possible in open fractures, or the fire had been active for a decade or more.

It has been advocated that "most remote sensing surveys should use light aircraft at times and in seasons which best amplify the contrasts (either tonal or structural) which are sought. Remote sensing should be a small-scale personal effort, strongly involving the geologist. He should have had sensor training, but only after a strong grounding in photogeological techniques. He must direct the programme, define its objectives, and personally be present during the data-gathering. Rapid availability of final data is essential, so that corrections in flying times and techniques can be made to achieve better the objectives", (Ref. 26).

4.4 Engineering Geology

Engineering geology may be involved in investigating ground (e.g. to choose the best site, or to record data that will help civil engineers design their works to cater for ground problems present) or searching for materials for construction. In some countries there are prospects of regional engineering geological maps being made on a national basis, rather than just local studies undertaken for a specific engineering project.

Multi-spectral scanning was tested for detailed engineering soils mapping (Ref. 27) and it was considered to be a useful supplement to air photography. The attempt to produce a soils map, using training areas for the computer to sense spectral signatures, was only a partial success. Laboratory reflectance measurements helped to understand the phenomena observed during the scanning, but did not give sufficient guide to make a reliable interpretation of the field measurements. The conclusion was reached that "much additional research is needed to quantify and predict the spectral and thermal properties of many soil types and textures under various conditions of moisture and irradiance".

Engineering soil mapping by existing photo-geological techniques involves extensive use of land-form analysis, and it is therefore necessary to have a stereoscopic facility or oblique 'lighting' to display the relief for the interpreter. Apart from the relief, other criteria used extensively are: drainage characteristics, vegetation, land use, tones and erosion characteristics. An MSS system providing data in the thermal range will help to resolve many ambiguities that beset the photo-interpreter. In particular it will help to indicate the moisture state of the soil which has an effect on the colour sensed in photography. The cooling effect of water should show in many cases, and it should help to distinguish between permeable porous soils and impermeable porous soils. For example, in many European environments a terrace of river gravels or sand adjacent to a clay soil will shown a distinct infrared anomaly due to the cooling effect of the moisture contained in the clay soil compared with the relatively dry, free-draining sand and gravel. A practical example of this is the existence of large numbers of glacial land forms in Europe. They may be easily recognised from their form, but often the nature of the soil of which they are formed may be uncertain to the interpreter. The availability of information on the water content will help to assess their broad suitability as materials, and their foundation characteristics. At the ideal wavelength it may also be able to produce information in vegetation covered areas where there is a relatively uniform plant life. If two adjacent areas are covered with the same plant species, then that portion of the area which provides freely available water for the plant roots may show on an airborne image as a cooler zone, for the plants will be taking up more water, and will be cooling more rapidly than in the dry area. In areas of residual soils this effect will also be of tremendous advantage to interpreters studying bedrock where there are contacts between rock types weathering into soils with dissimilar moisture characteristics.

Whilst rock identification can be done with existing photo-geological and spectral signature approaches, the state of the rock in engineering terms is also of interest. This can require the resolution of small fractures, perhaps only a few centimetres in width. An infrared study might give indications of the amount of moisture present. An example of sub-surface drainage obvious on infrared imagery (8-14 micron) has been shown (Ref. 28). This is extremely difficult, well nigh impossible, to detect from an air photograph of the same area taken with panchromatic material. This sort of information is of prime importance to an engineer studying a site prior to construction, and for some types of geological investigation may provide extremely useful information on bedrock conditions which may not be otherwise available to a surface investigator or photo-interpreter.

Varying ground moisture and micro-relief may be used to interpret the location of some types of unstable slopes. Old failures may show this situation exists, and could be of the order of 10m across with a varying surface relief of ± 0.5m on an old failure.

A low sun angle might be of possible help in micro-relief studies by which subtle changes in ground level may show subsidence problems for engineers, differential compaction over subsurface features, and instability in slopes. These sorts of effects may result in relief changes of 0.25 to 1m over an area of, say, 3m in the case of slope instability, or for subsidence over old mines or limestone sinkholes; areas of 10 or more metres across may occur in other cases

Subsidence over natural cavernous ground is a problem for engineering geologists. It is probable that infrared changes both in the photographic and thermal range will give indications of subsidence and collapse activity, drawing the geologist's attention to critical areas. It is less certain that the techniques can be relied upon to show incipient failure. Possible ways of doing this will be to detect changes in ground drainage conditions over near-surface collapse. This hypothesis has been tested but the results are not convincingly positive (Ref. 29).

Infrared imagery was used in a study of the San Andreas fault system (Ref. 30) as a contribution to the understanding of its earthquake related features. It was considered that imagery obtained one to two hours before sunrise was the most useful for the fault study, and the fault could be clearly traced over most of about 200 miles flown. Related moisture was the main cause of its detection - in some cases where the faults movement had acted as a sub-surface drainage barrier, and in other cases soil moisture changes were also significant as well as small changes in surface topography.

It has been reported that infrared line-scan has proved useful in detecting leaks from pipe lines, sewers, etc. (Ref. 31). This can be a frequent problem in areas of instability such as old coal mining areas.

4.5 Hydrogeology

General structural studies should help to indicate the position of water bearing structures. A study of drainage systems in both infrared and visible bands could give indirect evidence of aquifers and aquicludes from the location of springs, seepages, swallowholes etc. The density of drainage channels can be a broad indication of the permeability of surface material.

Near surface water and drainage routes can show as thermal anomalies. It has been shown that it is possible to make an assessment of the darkening of wet natural soils knowing the refractive index of the wetting liquid and the sample when dry (Ref. 32). Laboratory experiments at photographic wavelengths (Ref. 33) showed that the progressive darkening of soils can be at least qualitatively related to the amount of moisture present, but that when the amount of

moisture present is such that Atterburg's liquid limit is exceeded, then the relationshop breaks down.

In the study of prospecting for water in desert areas it was considered that remote sensors perform excellent reconnaissance in the search for ground water (Ref. 34). Infrared scanners, especially 8-14 μm imagery, must be included as a primary sensor. Less information is available in the 3-5.5 μm range. Good primary hydrogeologic reconnaissance is accomplished with the infrared line scanner (8-14 μm), and a horizontally polarised micro-wave radiometer at altitudes of 10,000m at night. To detail hydrologic conditions about a locality suspected as having buried aquifers, a multi-sensor programme at 3,000m or less altitude is best, with data collection both during the day and night.

An interesting problem under consideration in Britain is the monitoring of dam sites. There are many old dam sites scattered around the country that may be in an unsafe state and a regular detailed inspection of these is expensive. It is possible that regular monitoring by line-scan devices will show, especially in the thermal infrared range, the incipient failure due to leakage or seepage, and the presence of near-surface moisture in the dam. For satellite monitoring this is at present an extremely small target requiring a very high resolution and sensitivity, with the need for a means of isolating the imagery of the critical area concerned.

4.6 Surveillance of Volcanoes

The eventual possibility of monitoring volcanic areas with infrared scanning was foreshadowed when Hawaiian volcanoes were identified on Nimbus imagery (Ref. 35). The detection of the newly emerging volcanic island, Surtsey, from Nimbus II, has also been recorded(Ref.36).

The only prior evidence that all was not well with the Taal Volcano in the Phillipines was the rise in temperature of the crater lake during the three months previous to the catastrophic explosion. This rise was approximately twelve degrees from an annual average of thirty-three degrees centigrade, and the total was achieved in the first of the three months. This obviously indicates a possible important application for satellite monitoring, and as more quiescent volcanoes are now being instrumented, it is likely that further information will be acquired about the thermal effects prior to eruption. For the time being the most satisfactory periodicity for sampling temperature cannot be assessed without better documented examples.

It has been suggested that 8-14 μm is the best range for monitoring (Ref. 37), and that diurnal changes in surface temperature dictate that thermal anomalies would show more strongly against the background immediately before sunrise. Night-time surveys by aircraft often pose problems in the rugged terrain near volcanoes. Quite a number of infrared line-scan studies of volcanoes now exist, and the evidence firmly shows that this technique will show up thermal anomalies. There is however, lack of detailed ground and time studies.

Descriptions of infrared surveys of volcanoes of Kamchatka have been made (Ref. 38), and it has been concluded that this was an important way of monitoring volcanic activity, but that the maximum information about the structure of the volcanic source can be obtained only through concurrent interpretation of aerial photographs and infrared imagery. It was suggested that improvements are required in the interpretation of volcano surveys by the development of methods of quantitive analysis of the data.

Thermal effects can be observed indirectly in other parts of the MSS spectrum. Thus by a precise timing it is possible to examine the effects of ground temperature on the rates of snow melting, and changes in the vegetation cover can also show heat anomalies. These indirect approaches are likely to be less reliable than thermal surveys, as they are more critically dependent on timing in the case of snow, and in the case of vegetation may be too subtle and slow.

4.7 Geothermal Energy

A closely allied problem to the thermal studies of volcanoes.. prospecting for natural sources of thermal energy.

Miroshnikov et al (Ref. 39) have successfully used infrared line-scan to map potential sources of thermal power, and have found them to coincide with fractures.

It has recently been announced (Ref. 40) that sufficient potential thermal power to meet the present needs for electric energy in Ethiopia has been discovered with the aid of infrared line-scan airborne surveys.

5. INTERPRETATION PROBLEMS

The varying degrees of personal skill necessary for the interpretation of geology from photography and imagery are very thinly scattered through the existing geological community. Although image analysers are becoming available, their use in non-experimental projects is still small, and there is virtually no form of automatic data processing used in routine investigations other than the computer processing of data that has already been extracted from the image by a human interpreter.

Present procedures and personnel do not seem adequate to cope with the potential production of imaging satellites. The gap may be partly filled by automatic data processing either intended to be complete in itself or in a form that relieves the interpreter of those routine aspects of his work that can be formalised for machine treatment.

The advent of MSS makes some form of automatic image processing essential, for the human mind cannot hope to carry the data of more than 4 or 5 sets of imagery of different wavelengths.

The geology of every area is unique, and virtually every area produces new challenges. It may be possible to reach the stage where automatic data processing can perform some types of simple operation completely, but the best results in the majority of studies are likely to be obtained from an admixture of men and machines. For example, it seems already possible to process imagery to produce a plan of the surface distribution of exposed pure silica sand (Ref. 41); but proceeding from this point a good photogeologist using his knowledge of structural geology, sedimentation, geomorphology, plant ecology and the effects of the sand on slope stability and drainage, would be better equipped to interpret areas where there could be concealed material. Good interpreters have to be imaginative scientists keeping abreast of the mainstream of their subject which is still rapidly advancing.

The following subsections indicate some interpretational procedures.

5.1 Visual Inspection

This is routine practice for photointerpreters using stereoscopes to provide three dimensional images. The criteria they use is a mixture of ground phenomena (landforms, drainage features, land use and vegetation) and photo phenomena (texture, colour, tones and patterns). MSS will add new quantities to the latter group, and completely new data in the form of spectral signatures and thermal inertia indications from those parts of the spectrum that are not accessible to photographic techniques.

There are more problems in interpreting infrared line-scan than in normal photography (Ref. 42). For example the effects of atmospheric temperature and humidity on plant emission, the relation between surface leaf texture and emission, the effects of ailments on a plant, and the influence of changing temperature with height which can cause the leaves at the top of a tree to be warmer than those lower down are all factors of little relevance to reflective images.

However, there is surprisingly little written about the methodology of interpreting infrared line-scan, apart from the interpretation of obvious anomalies. The problem of producing infrared image mosaics for geological investigations has been discussed (Ref. 43), and emphasis was placed on the necessary care to be taken at the flying stage in order to produce results that can be assembled in mosaics.

It would seem that infrared line-scan can be assembled into mosaics for limited areas, but large regional studies are bound to be fraught with problems of time related temperature changes, and thus for investigation of large areas satellite scanning systems may come into their own.

There is of course, a considerable effort being put into automatic data processing, especially using digital processing, but there seems to be scope for investigations into the nature of patterns, shapes, etc. in terms of their geological significance.

5.2 Spectral Signature Mapping

Records of the thermal infrared spectra (Fig. 1) published by Lyon (Ref. 44) showed the possibility of using these unique responses as a basis of automatic interpretation of rock types, at least in areas of exposed rock. Thus by matching absolute or relative radiances at the points of the curve represented by the sampling channels of an airborne or satellite scanner, it was hoped that the unique characteristics could be a basis of automatic mapping. It was possible to map geological units by the use of digitized multi-spectral satellite photography (Ref. 45), with an 'excellent' correlation between the computer-classification map and the generalised geological map. However, it was found that several spectral classes were necessary in order to map adequately a single rock type with as many as ten spectral classes being assigned to a granite.

A recent paper (Ref. 46) shows there are absorption bands for ferrous and ferric iron in the near infrared that may possibly be exploited. Tests were carried out in the laboratory and using air photography, and the results seem sufficiently clear-cut to indicate that multi-spectral scanning can also be exploited at these wavelengths to distinguish rock types and mineral deposits having varying iron content.

Similarly silica, a key to many rock classifications, has absorption in a different part of the infrared that can aid in the distinction of a number of important rock spectral signatures.

One of the advantages of having a large variety of spectral bands available is the ability to tackle features in changing ground conditions. Thus the distinction between two adjacent rocks might be difficult where they are soil and vegetation covered. One rock may weather into a clayey soil which would show in the thermal bands due to being cooled by the moisture content, whilst distinction between the different types of vegetation growing might be more easily tackled in the photographic infrared where green plants show a considerably greater variation of reflectance than in the visible part of the spectrum.

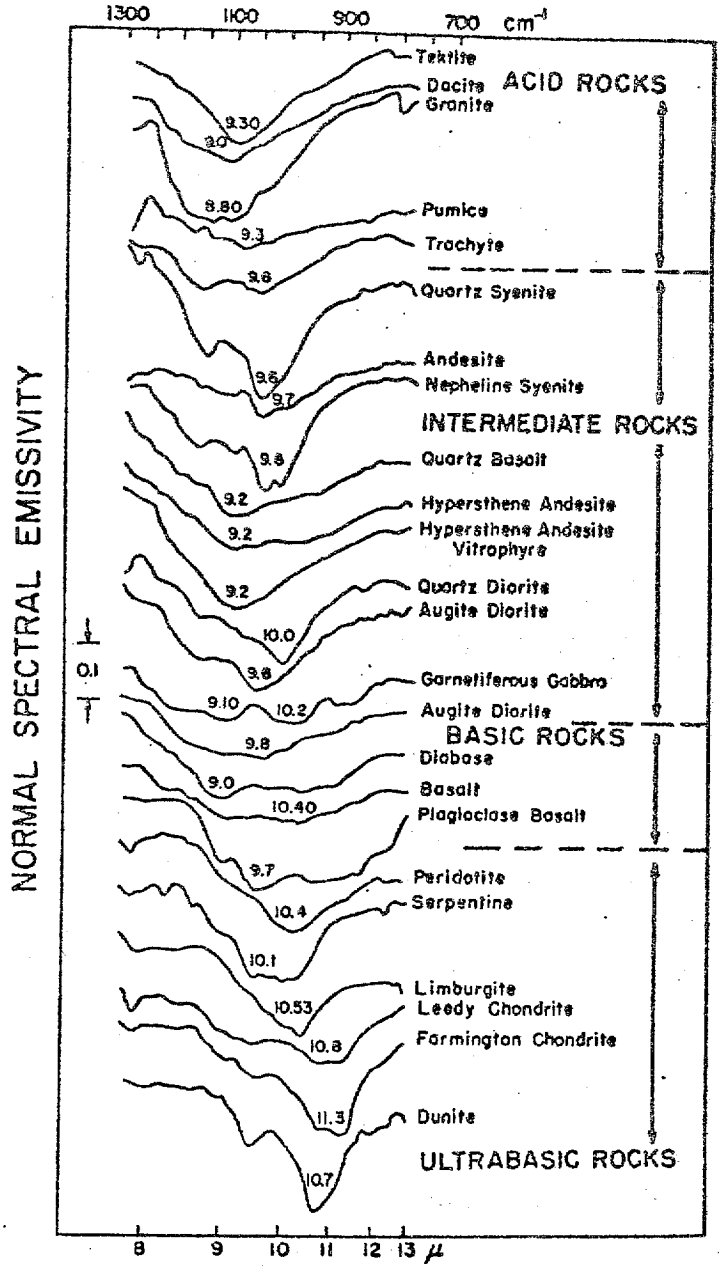


FIG. 1 Spectral normal emissivities of common terrestrial rocks, tektites, and chondritic meteorites, between 8 and 13 microns, as measured in the laboratory. Spectra arranged in decreasing SiO_2 content from 'acidic' to 'basic' rock types. Numbers refer to the wavelength of prominent minima. Specimen surfaces were either sawed or broken naturally. A relative scale of emissivity is given along the vertical axis. (Lyon, Ref. 44)

The approach to interpretation by way of spectral signatures may have more validity for geology in respect of bare rocks and soils, than it does for crops and forests which are ever changing. It seems that the most difficult type of terrain for automatic data processing of multi-spectral scanning will be that which is covered with soils and thick and varied vegetation. The appearance of vegetation can often be exploited, as it is at present with air photography, to determine the geology by inferring the conditions responsible for the current appearance of the vegetation. This takes two aspects, the present distribution of species may be due to long term selectivity, which means that when sufficient knowledge of the geological and other aspects of plant ecology are appreciated by an interpreter (or an automatic processing system), then this can be used to infer the general geology. A second approach is to study the individuals of selected species in order to assess their state of growth and health, and relate this to the underlying geology. For example, plants showing water stress may be situated over permeable well drained soil, whilst those showing toxicity may be present over natural sources of 'pollution', (e.g. base metal sulphide minerals). To exploit this latter procedure it will, of course, be necessary to be able to recognise plants of the selected species, and to isolate them sufficiently to make measurements of size, shape, reflectance etc.

Work on comparing ground and airborne measurements made from photography (Ref. 47) shows that there are variations in the results, commonly of a smoothing nature, due to such factors as atmospheric influences, environmental factors, averaging caused by resolution etc.

As rock and soils have a slightly varied appearance under different circumstances, it is likely to be best to use some type of training system for a computer in establishing a programme for mapping by local spectral signature recognition. The common agricultural approach of taking an area where all the soils and vegetation are identified in a 'truth site' is not necessarily the ideal in geology. The only certain identification of bedrock is at exposures or where there have been bore holes, wells, shafts etc. penetrating the vegetation and soil from the surface. The field geologist proceeds from exposure to exposure in such places as old quarries, the bottom of eroding streams, or cliff faces, and he extrapolates between these features by using geomorphology and various other kinds of evidence and reasoning. Between these sites the validity of his map hinges on his own intuition, ability and knowledge, and it is better for a training programme to be based on the observed facts rather than the inferred interpretations. It is therefore, suggested that if interpretation techniques for geological purposes are to be developed using a training system, they should be confined to a series of known sample localities rather than a continuous surface of area in which the geology between exposures has been inferred or guessed.

In a sense the spectral signatures will also have to be determined independently for geology in areas where the ground is covered with vegetation. Here it is probably best to aim at scanning at the best season to obtain maximum distinction in the vegetation to reflect underlying geology. This will in general be the same for similar terrain with similar climatic conditions, and analogies should be drawn from past experience after a limited amount of field testing or similar studies have been documented. The field work can then be limited to sampling bedrock in limited areas for a computer training programme, and this can be done after the scanning, which can be exploited to give an indication of where bare bedrock is likely to exist.

A normal requirement of field work for photogeology by classical techniques with air photographs, is the investigation of unknown patterns appearing on the photograph. It is to be expected that such patterns will also occur on M.S.S. imagery and the geologist's interpretational skill will have to be exploited for him to sense which features are related to natural geological conditions, and which are irrelevant, such as shadows, crop spraying, and old human activity. The normal practice in photogeology is to space one's ground control very widely, although possibly thinly, so that the photographic images are exploited for extrapolation between known bedrock outcrops. The same techniques would be best applied in MSS ground control, for an area may not contain a repetition of the same phenomena identified in the small patch used as a training area. Unsampled new rocks may exist anywhere in the study area.

An interesting experiment was carried out in Yellowstone Park (Ref.48) which involved processing a seventeen waveband set of results against results from training areas, and selecting the four most useful bands. With these the rest of the area was classified in terms of: bedrock exposures, vegetated rock rubble, glacial kame, glacial till, bog, talus, forest, surface water, shadows. The results were reported as 86% accurate, and a repetition of the experiment with a simulation of the E.R.T.S. imagery bands gave nearly as good a record. The thermal infrared results gave indications of the possibility of further sub-divisions in the mapping units, and, a critical feature for geology, it was considered possible that variations could be detected in the forest areas related to the presence of gravels over bedrock. In a similar manner, using the spectral reflectance of soils from thirty-six States in the U.S. (Ref. 49), it was shown that the information at five selected wavelengths (.40, .54, .64, .74 and .92 μm) produced sufficient information to enable the prediction of the reflectance at the other thirty wavelengths investigated. A further study shows that this is applicable widely, and consideration should be given to limitation of the number of channels scanned on surveys so that problems can be reduced at the processing and data storage stages.

The good results obtained in the Yellowstone Park experiment (Ref. 50) may have been due to the fact that the mapping units were easily distinguishable by the system in the area concerned. But the results of other tests (Ref. 51) showed figures for crop identification ranging from 75% accuracy down to 27%, and low percentage ground cover crops such as lettuce, onions, carrots and cabbage were indistinguishable from bare soil on satellite multi-band photography.

An allied technique is to use the statistical methods of cluster analysis to classify families of closely related spectral signatures, and use these for map production. This is analagous to some aspects of classical photogeology in that fieldwork would be needed to give rock names to imagery patterns.

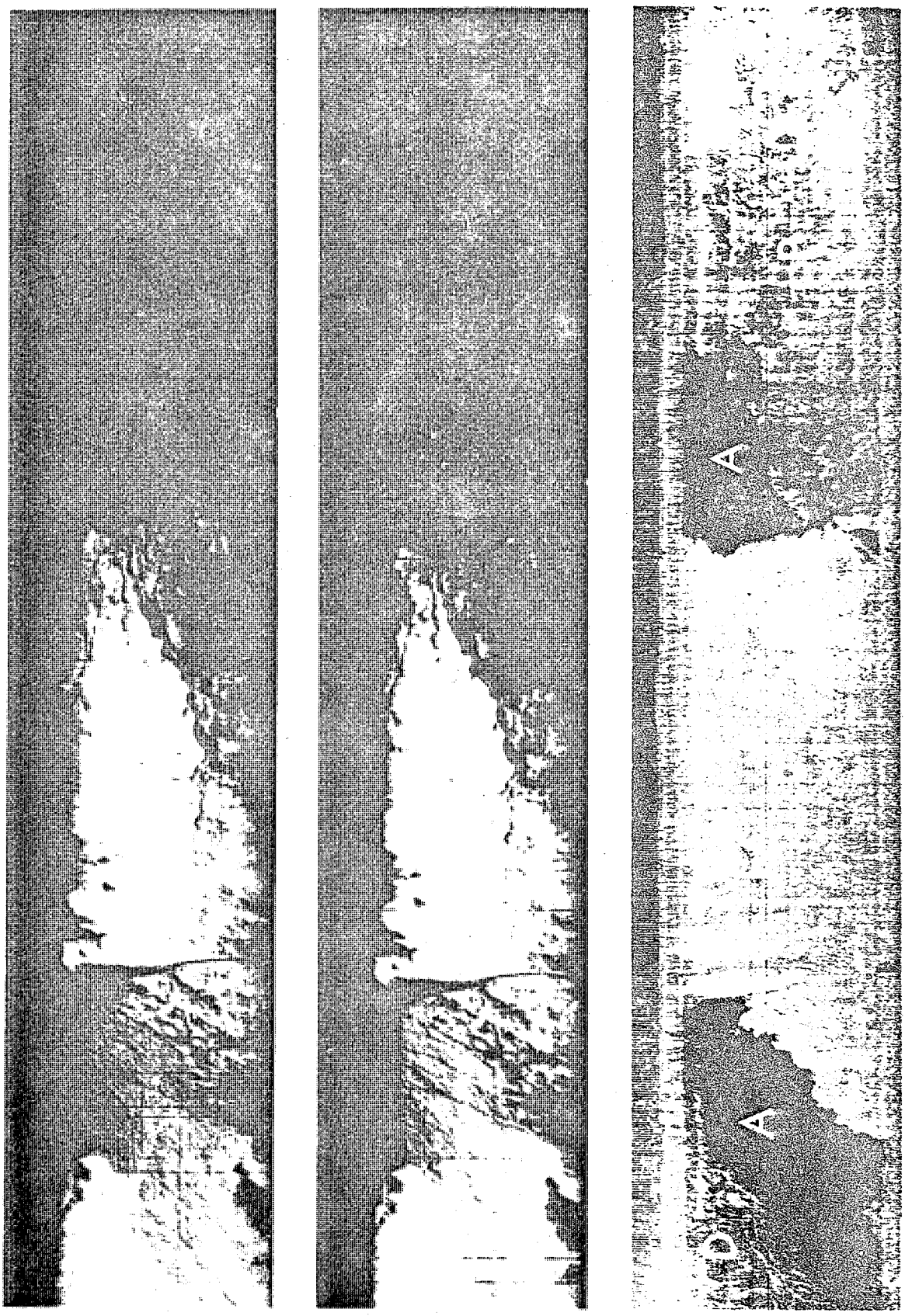
A terrain map consisting dominantly of geological features (Ref. 52) has also been produced by using a digital computer and clustering techniques with colour film as a 3-band sensor. The accuracy of mapping was "better then 85 percent and is slightly better than that of maps of the same area made by computers using multi-spectral scanner data gathered at the same time the photos were taken, even though the spectral resolution of this colourfilm method is inherently poorer than that from the scanner data, and the spatial resolution selected was slightly poorer than that for the scanner". In comparing the two methods of data acquisition, it was considered that colour film is inexpensive, distortion can be remedied by simple photogeometric techniques, and that the colour image is of considerable interpretative value in its own right. On the other hand the film has poorer spectral resolutions, and the wavelength range of the film is more limited than that of the scanner.

5.3 Ratio Mapping

A relatively new approach to the direct mapping of geological materials is the use of the ratio of the radiances of two critical wavelengths To a certain extent this corrects for some of the variables affecting radiances.

The approach was used in an experiment designed to aid the recognition of exposed quartz sand and sandstone (Ref. 53). A two-element infrared detector was flown over a sand quarry and the results analog-processed to produce a ratio image on which the exposed quartz sand and quartz sandstone were clearly identifiable. The results were also treated with a computer to remove noise and tape skew. The resulting computer map showed the targets more precisely.

Work in the Pisgah Crater (Ref. 54) took this method further by comparing infrared and visible wavebands to sense variations in iron oxides. Better results were subsequently obtained with the aid of a third channel, and the technique was also evaluated using photographs as the source of data,(Fig.2).



D: DACITIC MTS. A: ALLUVIUM. LA: LAVA. P: PLAYA

FIG. 2 Infra-red thermal emission images with an example of a ratio analogue, from an area near Pisgah Crater, California. (From Ref. 54).

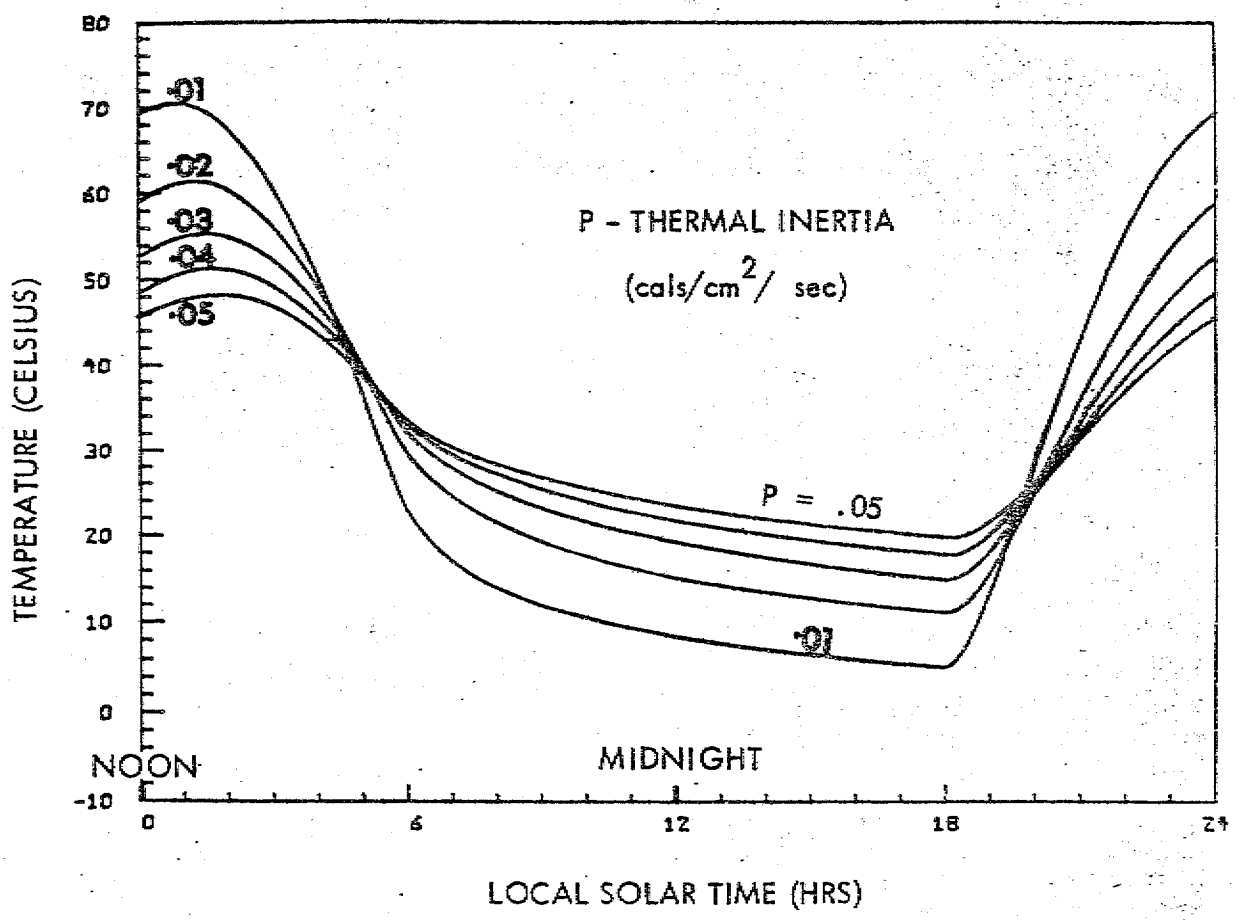


FIG. 3 Diurnal temperature variations of materials with different thermal inertias. (Pohn et al, Ref.56)

5.4 Texture Analysis

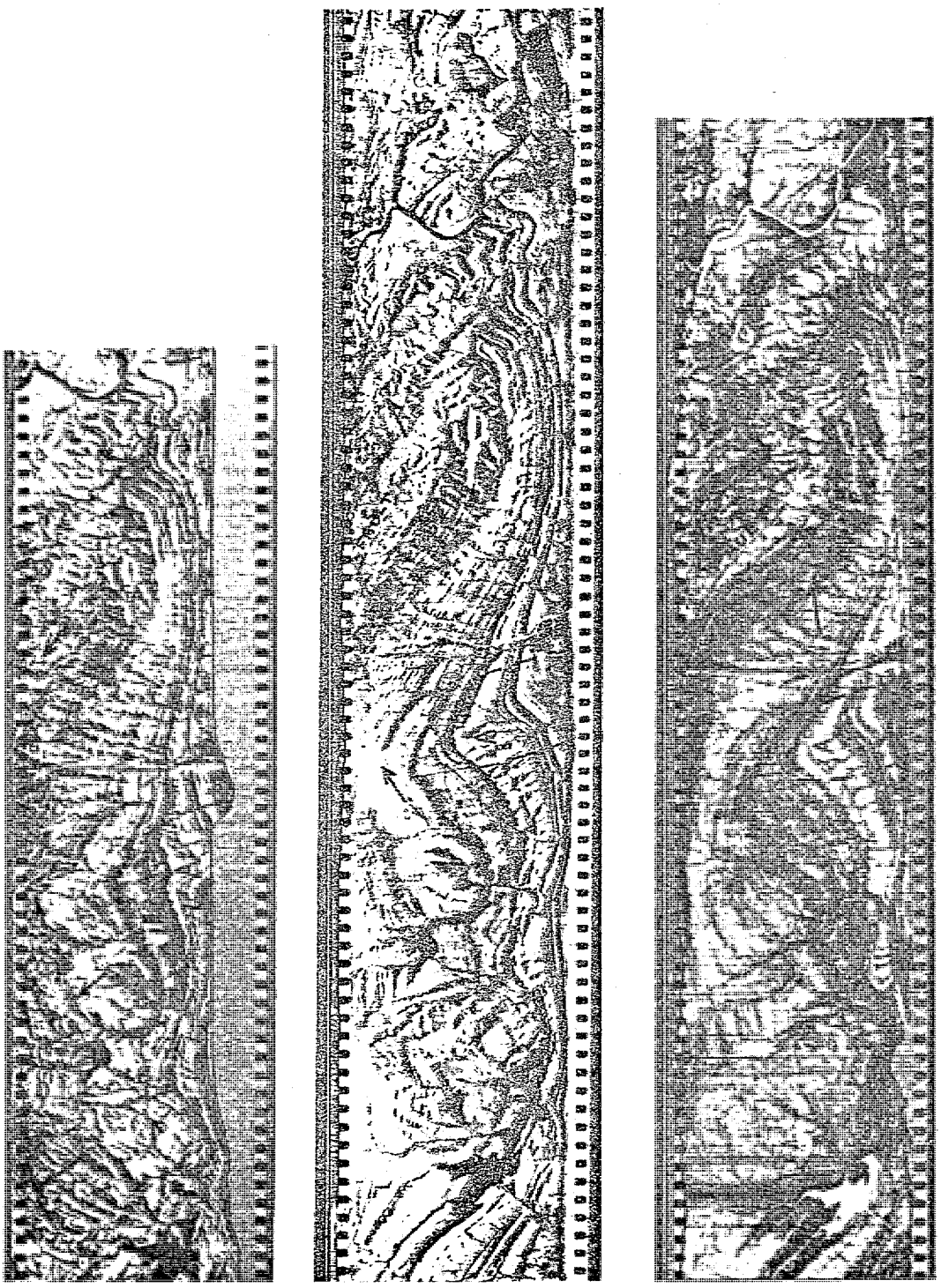
An interesting technique for geological applications is the automatic texture analysis described in a report (Ref. 55). While the reported experiment was primarily for vegetation analysis,it might also produce some useful information on picking out marker horizons inside larger units of a single exposed rock type.

5.5 Thermal Inertia Mapping

An interesting experiment has been described (Ref. 56) in which digital data from a Nimbus satellite radiometer (with a nominal resolution of about 8 km) was exploited to map effects correlating with desert rock geology. A relationship was constructed of the thermal inertia as a function of local day-night temperature differences, and this relationship was used to derive thermal inertias from the satellite observations. A reasonable correlation was obtained with rock units, certain inconsistency being explained by the geological map not taking into account the distribution of the superficial deposits. An unexpectedly anomalous area was later found to be due to the presence of a belt of dolomite and quartzite not recorded on the map that was available at the start of the experiment.

This approach may well be helpful in detailed studies with MSS Fig. 3 shows the nature of temperature changes related to thermal inertia.

Fig. 4 shows thermal images of a region at different times of the day demonstrating different appearances of rock types during the diurnal cycle.



A B C

FIG. 4 Infra-red images of part of the Arbuckle Mountains, Oklahoma, scale approx. 1:120,000; note temperature change effects in area A. Arrows indicate areas of prominent lineaments.
A - 11.00am image. B - 2.00pm image. C - 6.00am image.
All images show useful structural and litho-stratigraphy.
(From Ref. 62).

6. RECOMMENDATIONS

The following recommendations are based solely on the geological requirements and are based on the necessity to develop the following aspects of the MSS technique.

(a) The development of suitable instrumental performance.

(b) Testing the instrument under 'field' conditions.

(c) The training of a cadre of interpreters.

(d) The development of data processing techniques, and analytical instruments and processes that will enable the geological interpreter to extract the maximum amount of information from the data.

6.1 Instrument Development

The following need consideration:-

(a) Achieving a high degree of spatial resolution of ground features, if possible to be comparable with photography.

(b) There are indications that detailed information from a few narrow wavebands may be preferable to moderate information from a large number of channels, but the best number and location of these channels cannot yet be fixed with certainty.

(c) Providing stereo-imagery or a means of sensing ground relief.

(d) Recording different imagery simultaneously with calibration that will enable it to be compared and processed automatically on the ground. If possible, including a means of correlating different sorties including night and day imagery of the same terrain.

(e) Reducing installation and other costs so that it becomes economic to scan small areas from light aircraft as well as large areas from satellites.

(f) Producing imagery that can be used in image analysers with additive colour techniques and computer analysed displays.

6.2 Instrument Testing

Close collaboration between technologists and geologists is essential at this stage. The testing should be carried out in order to:-

(a) Determine the relative amount of geological data obtained:

i) in different environments (see later)

ii) at different wavelengths

iii) with different combinations of wavelengths

iv) at different times of day and season.

(b) Produce imagery correlated with geology that can be used to establish interpretation criteria.

(c) Establish if unexpected ground factors are affecting the results.

(d) Find the causes of anomalous results or noise, and see if they can be suppressed, tolerated or exploited.

6.3 Interpreter Training

Until instrument designs are standardized and the number of channels and types of image analysers tend to stabilize, it is difficult to determine whether we have to plan for individual interpreters or teams of specialists. The requirements for first class interpreters will involve such a wide knowledge, with continuous updating, that any deliberate training programme will be long. Photointerpretation is in the nature of a science based skill or craft, and after limited formal teaching, needs to be practiced under an experienced supervisor. At present this means learning in industry (e.g. in an air survey company), or at a postgraduate teaching course, or during a research programme for a higher degree study.

For the time being preliminary experience can be gained from multispectral photography and existing equipment, but the ideal way of handling this material is still being explored. It seems therefore that a preliminary emphasis is needed on research into interpretation techniques with MSS and that this should also be done with the possibility of using some results to set up training programmes and establishing interpretation criteria and/or software for future interpreters.

It is suggested that an early effort should be made to:

(a) study existing data,

(b) do correlative studies between imagery and geology at test sites,

(c) publish the results of (a) and (b) in an accessible and easily understood form for all potential interpreters.

6.4 Automatic Data Processing

The vast quantity of data produced by an M.S.S. aircraft or satellite system will take intolerably long to exploit if we use only human beings for survey interpretation. Some kind of man-machine capability is required, especially during the period of instrument and interpretation development. It is recommended that any start in this field should be aimed at producing approaches that are flexible enough to adapt to a variety of wavelengths.

Analysis of spectral signatures is initially likely to yield more reliable results than automatic spatial pattern recognition and initial work should be easiest in desert areas where at least the confusion of vegetation and human influence is minimized.

There is immediate potential in developing processing techniques for data that has either been confined to a simple, limited machine procedure for analysis and presentation to an interpreter, or data that has been already interpreted by a human being but requires further processing. These alternatives could later become part of a fully or partially automated system. For example, the automatic extraction of the distribution of a vegetation group might be made, and its various significances deduced by human decisions; alternatively an interpreter's version of the location of fractures could be machine processed to establish the significance of their relationships and areal distributions. Most interpretation with photography has resulted in a research project for each area, and attempts at producing comprehensive 'keys' for geological interpreters have only had local success. Each study involves originality,accompanied by extensive geological experience. The work is always done by geological graduates - those involved in the work do not seem to accept the possibility of technician training from 'keys', and this bodes ill for computer training for fully automated work. A major aspect is that the photogeologist uses indirect evidence to interpret the subsurface geology that the sensor cannot see.

6.5 Ground Truth Requirements

It has been pointed out (Ref. 57) that there can be a wide gulf between the expectations generated by laboratory experiments, and practical results obtained under flying conditions. For example, the rock and soil spectra in the near infrared are not very comparable (in contrast to laboratory data) with results obtained at jet aircraft altitude and speeds in a reported experiment (Ref. 58). It therefore seems essential that testing should be done in normal field conditions in which a wide variety of circumstances are represented. The laboratory has its role, but in geological testing it should be a minor one.

One of the problems in laboratory measurement of material characteristics is that many are determined with specimens that are not truly representative of field conditions. Now that light-weight spectroradiometers can be taken into the field, it is to be hoped that this situation will improve. But it must be remembered that rocks and soils are not pure chemical precipitates, but often can grade into other forms. Thus a conglomerate can change laterally into a sandstone, and further away into a shale, and then into a limestone,

with a resulting gradation and interlayering of materials. Similarly an engineering geologist may find in a limited distance varying mixes of the same minerals, giving in his terminology several soils such as a silty clay, a sandy silty clay, a clayey sandy silt, a clayey silty sand etc.

Information is obviously required on the influence of the column of air beneath a satellite on the spectral signature of rock soil/vegetation targets. Some experiments could probably precede satellite studies by exploiting aircraft or even distant ground observations in selected monitored atmospheres.

Work by Watson (Ref. 59) has shown that there are distinct differences in the reflectance between fresh and weathered rock surfaces which are further modified by the effects of lichen growth and moisture. The nature of weathering effects on rock surfaces is in turn a function of a variety of factors such as the direction of prevailing winds and of rainfall, extremes of climate temperature, amount and type of vegetal cover, drainage conditions, etc. This list does not consider variations within the rock itself such as varying grain size of the minerals, slightly different mineral contents, difference in physical layering due to the conditions at the time the rock was created or orientation of the layering in relation to the ground surface. These are only some of the factors affecting its likely appearance, and this list is formidable enough. It seems desirable therefore, that apart from broad generalities, work aimed at mapping the distinction between many rock units may be best achieved by having some operation relating to the actual scene of the study and that spectral responses will have to be determined from sample areas within the survey district.

Good experimental test ranges can be made to serve a number of purposes:

1) The objective determination of the types of geological features which can and those types that cannot be sensed and distinguished by MSS under different conditions.

2) Testing interpretation techniques, data processing, etc.

3) Testing different sensing systems and modifications.

4) Building up geological interpretation criteria data files.

5) Training interpreters with proven ground control.

6) Resolving the effects of different physical parameters on the final image under 'field' conditions.

7) Testing the effects of imaging at different times of day.

8) Objectively comparing the geological effectiveness of MSS with other sensors such as multi-spectral photography, side-looking radar and imaging microwave radiometers.

9) Determining whether multisensor missions are needed for any geological targets, and which sensors would be the best choice.

10) Comparing the results of airborne and satellite systems.

There are other obvious problems common to all disciplines (e.g. the influences of the column of air below the sensor; the effect of microclimate, etc.). These are not considered separately in the geological context.

Testing devices with airborne and satellite techniques is so expensive that it is imperative that careful thought be given to the choice and use of testing areas so that the maximum benefit can be obtained. Table No. II lists the ground parameters that need testing. These are derived from photogeological experience, but represent groupings to be considered for all types of remote sensors.

TABLE II

Ground Variables that can affect the Appearance of Geological Features on M.S.S.

Rock Type	Soil Type	Land Use	Relief	Climate Type	Time
Igneous Metamorphic Sedimentary (Hard) Sedimentary (Soft)	Residual (Derived from under- lying rock) Transported a) by wind b) by ice c) by water. Bare rock	Agriculture Open Grass- land Forest	Mountains Hills Plains	Hot Desert Cold Desert Temperate Mediterranean Moist tropics	Season. Time of day.

Each item needs to be combined with those in adjacent columns. Thus hard sedimentary rocks may show differently when under residual soil in a desert compared to temperate regions. This creates a forbidding list of combinations, but it should be possible to find many of the subdivisions in each test range, and only the 'climatic' column requires a mutually exclusive list of geographical locations. The 'Time' element involves mainly vegetal and sun angle effects at reflection wavelengths, and diurnal temperature changes and thermal inertia at emission wavelengths.

Multivariate statistical techniques can be employed to draw a wide range of inferences from each area (Ref. 60). Inevitably, the selection of areas raises problems as reliable data, particularly subsurface data, is essential. Bored and drilled ground has been sampled only at isolated spots and for other purposes, so that the required range of

parameters for MSS have been incompletely recorded. What changes exist between drill-holes in soil covered areas can only be guessed. Coastlines with cliffs give the most reliable situation, for here the soil and underlying rock can each be seen in cross-section. Inland extrapolation by surface ground mapping in the zone adjacent to the cliff will be relatively reliable. The deeply incised valleys in alpine areas should also produce enough ground control. The best final choice cannot be made on the basis of a desk study, for although there are many areas mapped in detail, the data recorded have been in terms of relative rock ages, rather than rock properties. Soils are often not recorded. This means that only provisional suggestions can be made. These need to be checked by a rapid ground study - say a quick reconnaissance tour of 2 weeks per area would confirm suitability. A detailed recording of rock and soil properties will be needed so that every fault, rock or soil change or other definable feature of geological significance is recorded with the full details of soil cover, etc. This can be done before imaging or after. It will then be possible to count the number of features showing and not showing in each area, and the ratio will be a rough measure of the sensor's usefulness to geologists. The same ground data can be used to determine the relative performance of different systems and sensors. It could further be exploited to show the effects of seasons, sun angles, wavelengths, time of day, etc. and to record how significant geological features appear on the imagery under different conditions, but the repetitive scanning could probably be confined to restricted sections chosen after studying the first results.

A further visit will be needed to the test areas after the imagery has been studied, for there will be unexpected effects caused by ground features on the images. This part of the study may be the stage at which new applications and ideas will emerge if undertaken by widely experienced geologists alert to society's and the professions' needs.

Test sites have been provisionally chosen with the intention of each case involving a single long run being made by the aircraft, but large embayments on the coast may make local diversions necessary; image data of the sea bottom and tidal flats will also be of interest. River estuaries should also be included for sedimentation studies and preflight ground studies may eliminate some sections. The European sites suggested represent Mediterranean, Temperate, Cold Desert and Alpine environments. It is necessary to look further afield for a hot desert and a rain forest environment. The areas suggested coincide with those suggested in a previous report on Side Looking Radar. This choice has been made on the basis of geological and not sensor requirements.

North-east England and Eastern Scotland

Position:	From Kinnairds Head (Scotland) to Flamborough Head, (England).
Distance:	About 500 km.
Climate:	Temperate
Relief:	Gentle hills, local small plains.
Rocks:	Metamorphic Schist and Gneiss, granite, lavas, palaeozoic and mesozoic sediments, glacial soils and alluvium

Geological Maps:	All ground covered at 1:63,360 and at 1:10,000. For much of the English section all parameters at the sea cliff are available on punched cards(Ref. 61).

Iceland

Position:	Approximately North-South from Húsavík to Vík.
Distance:	About 250 km.
Climate:	Cold desert.
Relief:	Plains and hills with glaciers.
Rocks:	Basalts and other lavas; tuffs, sediments, glacial and alluvial deposits. Volcanic vents. Some slope failures and fracture zones. (Iceland is subject to active research for evidence of 'floor spreading'. It is at the parting of two large crustal plates). Large areas of exposed rock of varying textures are present.
Geological Maps:	Good published maps exist for about ¾ of the route at small scale.

Alps

Position:	Lyon - Torino.
Distance:	Say 250 km.
Climate:	Temperate with cold desert at high altitude.
Relief:	Mainly mountains and hills,some plain. Some forest.
Rocks:	Granite, metamorphic schists and slates, mesozoic limestones, sandstone and shale. Unconsolidated quaternary sediments. The sequence includes graphitic rocks and there are complicated major structures.
Geological Maps:	Mainly 1:50,000 and 1:80,000 in France and 1:100,000 in Italy.
Access:	A main route exists, but fieldwork will be a slow, tedious process.

Arabia

Position:	Jeddah and along escarpment to North-west.
Distance:	About 200 km.
Climate:	Hot desert.
Relief:	Irregular escarpment rising out of coastal plain, of the order of 2000m., reducing northwards to groups of hills under 1000m.

Rocks:	Plateau basalt, meta-volcanics, acid and intermediate intrusive igneous bodies. Some possibly minor copper mineralisation. An extension inland to the south-east could include a massive pyrite deposit at Wadi Wassat. A nearby diversion could include the hot brines and metal deposits in the Red Sea that are currently exciting scientific circles.
Geological Maps:	Good reconnaissance at 1:1,000,000 scale exist. Ground mapping is now in progress and should be near completion by the time of testing. The publication scale is not finalised, but may be 1:100,000.
Access:	A coastal road gives general access to foot of escarpment. Wadis give access for vehicles at intervals.

Tobago (West Indies)

Position:	The coastline.
Distance:	About 80 km.
Climate:	Wet tropical (Forested).
Relief:	Hills of 100 - 300m.
Rocks:	Coral, clays, sands, marl, lavas, diorite and ultra-basic intrusives, phyllites, schists and metavolcanics.
Maps:	Geol. map at approx. 1:100,000 scale in 'Geology of Tobago', by J.C.Maxwell, Bull. Geol. Soc. America, Vol. 59, 1948, pp.801-854.

West Coast of Sardinia

Position:	Say from P. Caprara in the north to C. Spartimento in the south.
Distance:	About 250 km.
Climate:	Mediterranean type.
Relief:	Hilly with some plains.
Rocks:	Lavas, tuffs, granite, palaeozoic, mesozoic, and tertiary sediments, pleistocene and recent deposits.
Geological Maps:	Most ground covered at 1:100,000 or 1:25,000 scale.
Additional possible areas:	Two interesting areas to cover on return would be: (a) more of the Iglesias district where metal mines are located in areas of greatest strain in the rocks. This may show on a study of fractures and vegetal changes. (b) In the north-east of the Island there is a large mass mapped as 'Granite'. The characteristics of MSS might be tested in an attempt to subdivide this area into generations of granite. This would be a useful exercise, as in some parts of the world mineralisation (e.g. tin) is only associated with one generation of granite in a local suite of granites.

7. CONCLUSIONS

The growing use of infrared line-scan from aircraft seems to indicate an increasing acceptance of this technique by geologists.

Equipment exploiting the photographic wavelengths has not been available long enough to judge its effectiveness in comparison with photography, and this comparison cannot be done fairly until much more development of interpretation procedures is accomplished.

However, the large number of wavelengths exploitable, and the greater flexibility of taped data for interpretation might give MSS eventual technical advantages.

There are non-geological reasons (based on data transmission and recovery problems) for preferring line-scanning devices in satellites.

The variety of information that can be obtained by scanning appears to give MSS a greater geological potential than any other single imaging sensor at present in sight.

Although there is obviously a vast amount of work still to be carried out in the laboratory and in the field on absorption bands and spectral signatures etc., the way ahead may now be clear for progressive research to test, and hopefully, to bring multi-spectral scanning in desert areas to a state where mapping of bedrock types can be carried out in ideal situations.

In considering the geological future of multi-spectral scanning it is desirable to consider the long term future programme. The production of new equipment to map the immediate surface of rock and soil will not necessarily be received with such enthusiasm in the well-mapped countries of Europe, as would an instrument which could show subsurface conditions that are not readily detectable by ground inspection. This will involve applied ingenuity on behalf of geologists rather than physicists or engineers. Effort must be put into the establishment of interpretation criteria which will allow the imagery interpreters to make inferences of conditions below the surface materials identified directly from the scanner.

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MAPPING OF LINEAR STRUCTURAL ELEMENTS FROM REMOTE SENSING IMAGERY

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ABSTRACT: Remote sensing imagery is utilized in analyzing linear elements in structural geology. Some cautions in the use of the imagery are outlined. In two cases—the Bighorn and Laramie Mountains, Wyoming-linear features have been counted, and analyzed as to orientation. The orientation of folds and faults in the area west of the Laramie Mountains is closely controlled by the linear elements in the Precambrian basement. Folds in the Bighorn basin show little relationship in orientation to the linear features mapped in the Bighorn Mountains.

INTRODUCTION

Regional structural relationships in the Rocky Mountain area have intrigued many geologists, and resulted in a variety of syntheses. Among the many papers presented on this topic are those of: Ransome (1915), Chamberlin (1919), Mansfield (1927), Clapp (1932), Billingsley and Locke (1941), Chamberlin (1945), Thom (1959), King 1959), Badgley (1965), Eardley (1962), Blackstone (1963), Sales (1968), Stone (1969) and King (1969).

The syntheses and analyses noted above have been based on available geologic mapping at the time, and the personal knowledge and experience of the particular writer. In general the geologic maps available for use in regional studies have provided incomplete coverage, and in many cases a minimal amount of detail. Geologic map coverage of the Rocky Mountain region has steadily increased, and the quality of mapping has improved, and now the standard reference map for any regional analysis is usually the geologic map of a state at a scale of 1:500,000.

The preparation of regional maps can be a tiresome and frustrating process because of the wide variation in scale of maps, and degree of detail.

TYPES OF STRUCTURE DEPICTED

The conventional compilation of data in the form of geologic maps tends to emphasize major fold systems, broad regional swells and basins, faults, and distribution of igneous rocks. Limitations are usually placed on faults based on the linear extent relative to map scale.

Inferences relative to regional relationships are often drawn from such maps, and the tendency is to "see" geologic alignments, that are tenuous and often very difficult to document on the ground. The result is to create small scale maps with structural "lines," "trends," "lineaments," etc., that are dubious at best.

Regional structural contour maps using deep horizons (i.e. Cambrian-Precambrian interface) as a datum usually provide a more conservative, and perhaps more realistic overview of the major structural elements.

ROLE OF LANDSAT IMAGERY

With the advent of remote sensing imagery derived from the LANDSAT program new approaches to certain aspects of regional structural geology can be considered. Inasmuch as any type of imagery (black and white photography, colored photography, various sensor bands) provides a direct view of a segment of the earth's surface, there is available a data source at several scales from which geologic interpretation can be made. Geologists who have been engaged in serious field mapping are well aware of the potential that black-and-white stereo-photography provides for enhancing and enlarging the scope of day-by-day ground traversing over outcrops. Color photography offers the same potential, at a slightly more sophisticated level.

The limitations of usual moderate elevation, black-and-white stereo-photographic coverage for geologic mapping is that only a small area is covered by a single photograph. The construction of mosaic maps to obtain a greater aerial coverage denies the observer the use of the stereographic image.

Imagery from the LANDSAT satellite has the opposite level of usefulness. The single image has automatically "mosaiced" a large area, but denies the observer any stereographic effect. The large area covered by a single image provides an opportunity for the knowledgeable interpreter to critically examine the mutual relationships of large rock masses with the minimum of preparation of material. The image can be supplemented by any geologic ground mapping previously done, with the result that the interpreter's understanding of regional features can be greatly enhanced.

TERMINOLOGY FOR LINEAR ELEMENTS NOTED ON IMAGERY

The present writer has long been tempted to write a paper, the title of which might be "Lineament—a Journey in Semantics."

The term lineament was introduced by Hobbs (1904, p. 485) and an excellent discussion of the term is found in International Tectonic Dictionary—English Terminology, Memoir No. 7, Am. Assoc, Petroleum Geologists, John Dennis Editor—1967. The variations in use of the word indicate that it should not be used to describe linear features noted on various types of remote sensing imagery.

The writer has used the term "photo linear elements" (Blackstone, 1973) to describe any markedly linear *geologic* feature which might be observed on any type of imagery obtained from either aircraft or satellite. Used in this sense there is no genetic implication concerning the feature noted.

Hoppin (1974) has presented an excellent review of the use of the terms lineament and linear, which should be read by all individuals engaged in regional tectonic studies. The use in the present paper is essentially the same as that proposed by Hoppin.

Data of this type are abundant, and if treated with due respect until previous ground observation is reviewed, or

new observations are made can yield significant aid in the interpretation of the regional structural aspects. The data should be treated as clues or leads for further investigation, and not as absolute solutions to structural problems.

COMMON TYPES OF PHOTO LINEAR ELEMENTS

Fracture Systems

Imagery of areas of crystalline Precambrian rocks reveals extensive patterns of linear features which are interpreted to be the topographic expression of fracture systems. Limited ground observation confirms that the features are indeed major fracture systems. The sun angle is important in how well defined the topographic expression is upon the image. Light snow cover enhances the topographic expression.

Fault Traces

The traces of some known major faults or groups of faults can be seen on the ERTS images. In some cases projections of known faults laterally beyond the limit of established geologic mapping is possible.

Outcrop Patterns

Continuous hogbacks are expressed as linear elements, and are so common as to need no comment.

Aeolian Features

Active dunes and sand stripes vary from very marked clear cut features, to very subtle ones. Edges of dune fields commonly are sharp and well defined and appear as strong linear elements. Less well defined are the narrow, low relief, vegetation covered sand ridges that give a subtle linear character to some areas. Further study is needed of such cases.

Drainage Alignment

Streams seem inherently to take advantage of all differences in rock composition, and structure in establishing their courses. Such aspects as a regional joint system, fault traces and strike direction in rocks with very low dip are exploited by streams in the erosional cycle.

The remote sensing imagery provides a refreshing overview of the total drainage pattern of an area, which often emphasizes aligned drainage patterns that do not stand out on the usual topographic maps. The geologic reason for the alignment may not be immediately evident, but the imagery provides the clue for future investigation.

TECHNOLOGICAL GREMLINS

The individual using remote sensing imagery must become aware of aircraft contrail shadows, match lines, scanning variation in density of image, sun angle effects, etc. Some apparent linear elements may not be yet pinpointed as technological problems.

USE OF PHOTO LINEAR ELEMENTS IN STRUCTURAL INTERPRETATION

Orientation of Stress Field

Major conjugate systems of well defined fractures should provide a reasonable approach to determining the general stress field existing *at the time* of the deformation. The evaluation could be applied to the crystalline rocks of the Precambrian basement, or to folded sedimentary sequences of younger ages.

Differentiation of Periods of Deformation

A potential use of photo linear elements in structural analysis could be the differentiation of periods of deformation. If two periods of deformation have markedly different orientations, the fracture systems generated would be expected to likewise show systematic differences. The possibility of using this approach will depend upon the magnitude of the fracture system developed, and the resolution obtained in the imagery. To date this approach has not been seriously investigated.

The orientation of fold and fault systems may provide clues to episodes of deformation. Conventional small scale geologic maps do not provide a very effective tool for differentiating episodes of folding. The LANDSAT imagery provides an overview, in which relationships can be more fully evaluated. Further testing of this utilization of imagery is in order.

ROLE OF BASEMENT CONTROL IN LARAMIDE DEFORMATION

Basement control of large scale structural elements within the central Rocky Mountain region has been discussed by many writers. The advent of LANDSAT imagery has provided a new opportunity to review the problem. The Precambrian crystalline basement rocks in the exposed cores of the uplifts have been sufficiently etched out by weathering at high elevations to make major fracture patterns visible. Rose diagram plots of the strike of the photo linear elements in the crystalline rocks can be compared with the trend of structural features in the overlying sedimentary rocks in the adjacent basins.

Laramie Mountains

Two such studies have been done by the writer (1973a, b). The studies revealed a very good agreement of the two sets of values in the Laramie Mountains and the Laramie Basin. A comparison of fold trends in the Bighorn Basin with photo linear elements in the Bighorn Basin showed very little agreement. The conclusion based on these two cases is that basement fractures do not always act as a control on Laramide features.

Linear structural elements in the Laramie Mountains of Wyoming were compiled using LANDSAT imagery. A map of the elements, Fig. 1, is taken from Blackstone (1973a). Rose diagram plots the trend of the photo linear elements as shown on Fig. 2. A comparison of these plots

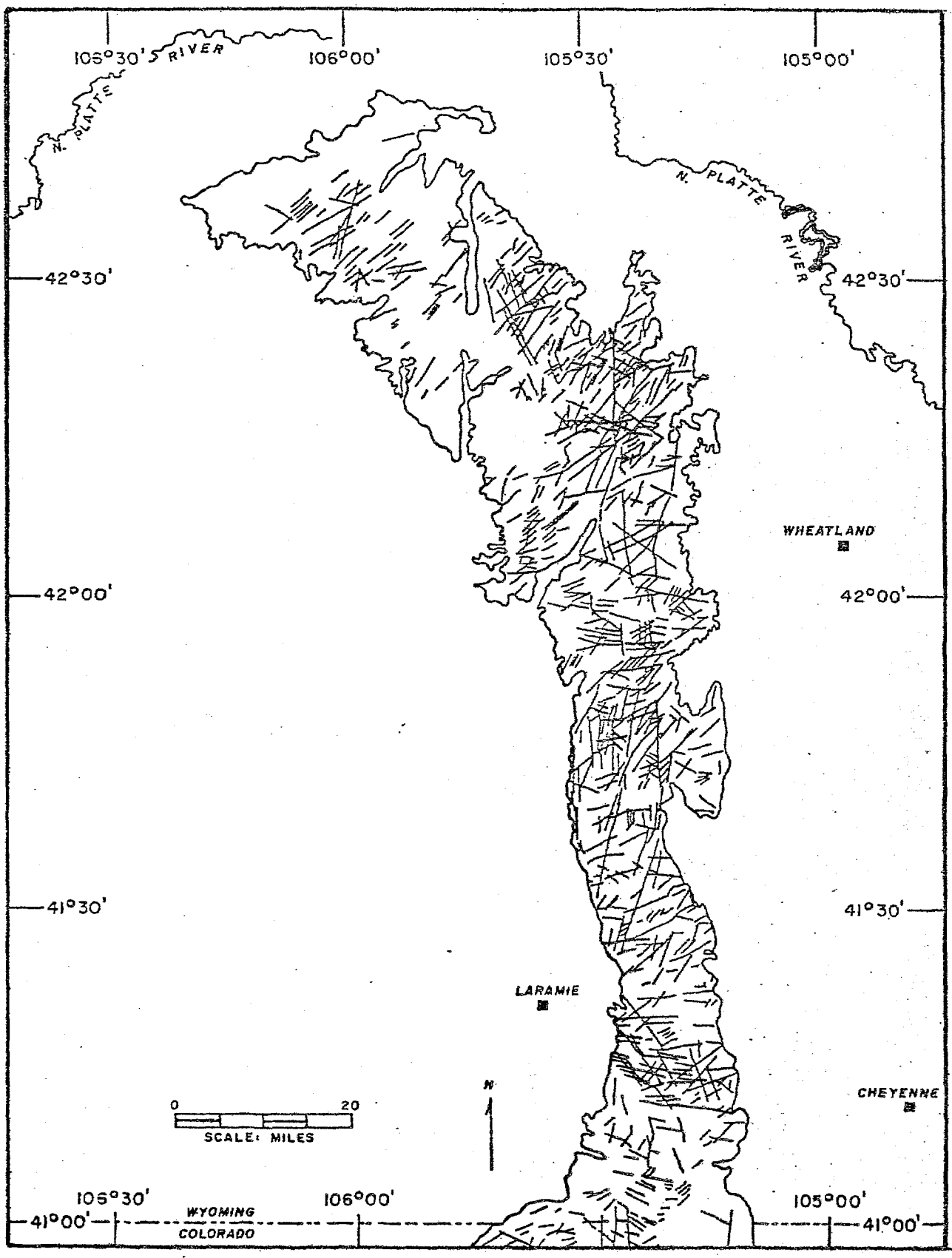

Figure 1. Photo linear elements of the Laramie Range, Wyoming.

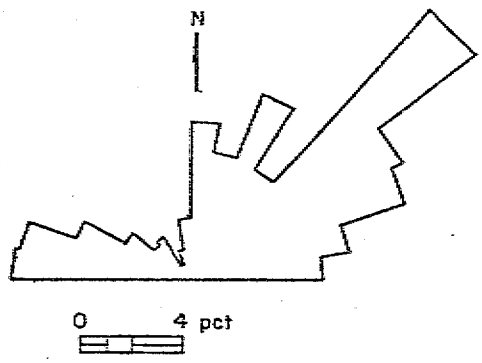

Figure 2a. Rose diagram showing dominant orientations of photo linear elements of the southen Laramie Range.

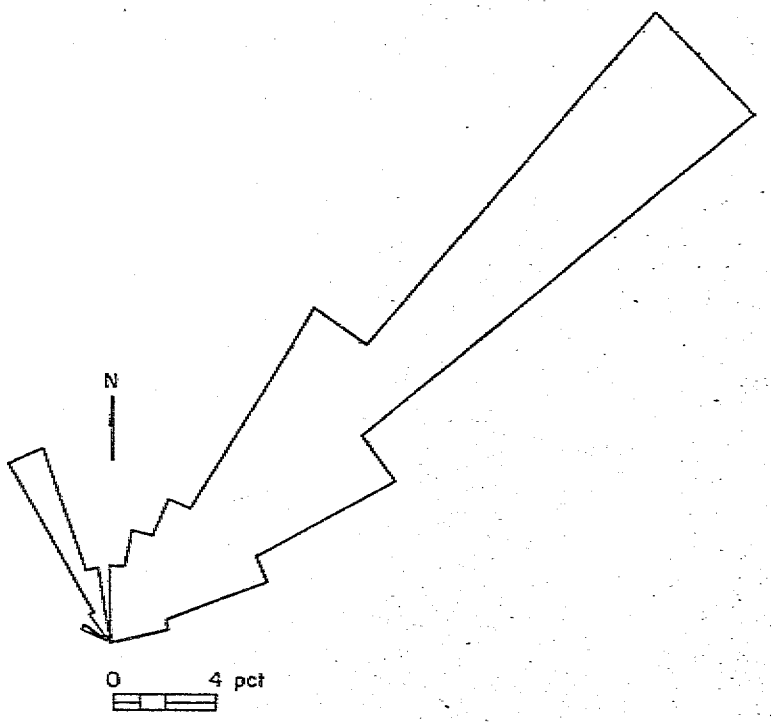

Figure 2b. Rose diagram showing dominant orientations of photo linear elements of the northern Laramie Range.

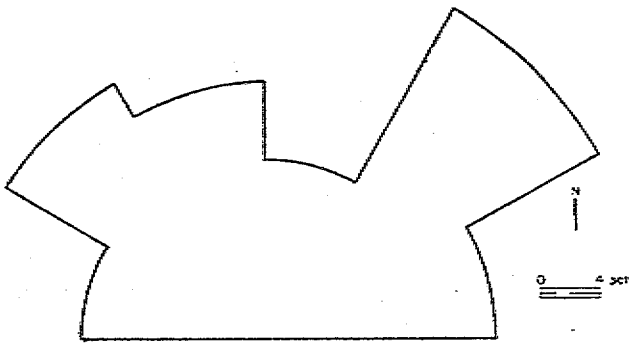

Figure 3. Rose diagram showing dominant trends of fold axis (surface and subsurface) Laramie Basin, Wyo.

with the fold and fault pattern of the Laramie Basin was prepared by Bekkar (1973), and reveals the control which the basement fractures exert on structures in the overlying rocks.

Bighorn Mountains

A similar study of photo linear elements in the Bighorn Mountains of Wyoming and Montana has been conducted. The map depicting the photo linear features is shown on Fig. 4—(Blackstone, 1973b). A comparison of the orientation of these elements with the trend of 48 fold axes in the Bighorn Basin is shown on Fig. 5. The conclusion from those data is that the fracture patterns of the basement rocks have exerted little control on the orientation of the deformed sedimentary rocks which overly the basement.

GEOMORPHOTECTONIC PROBLEMS

All major drainage adjustments such as piracy, superposition, and stream offsets due to fault control can be studied more readily by use of remote sensing imagery than by other compilations of data. In many situations the distribution of Quaternary deposits, (alluvium, pediments, glacial debris) is evident on the imagery and aids in interpreting the geomorphic history. The study of high level erosion surfaces which have been a long standing problem has not been materially aided by the use of the imagery.

SUMMARY

The use of LANDSAT imagery has not seriously changed known geologic ground truth in the area of Wyoming. The imagery has however provided a new, refreshing and stimulating overview of many older problems. This overview should lead to new understanding of regional relationships, and to encourage us to try new comparisons of data. As with any new data gathering system, some time is required to develop a new perspective. Once this perspective is acquired we should anticipate some stimulating results.

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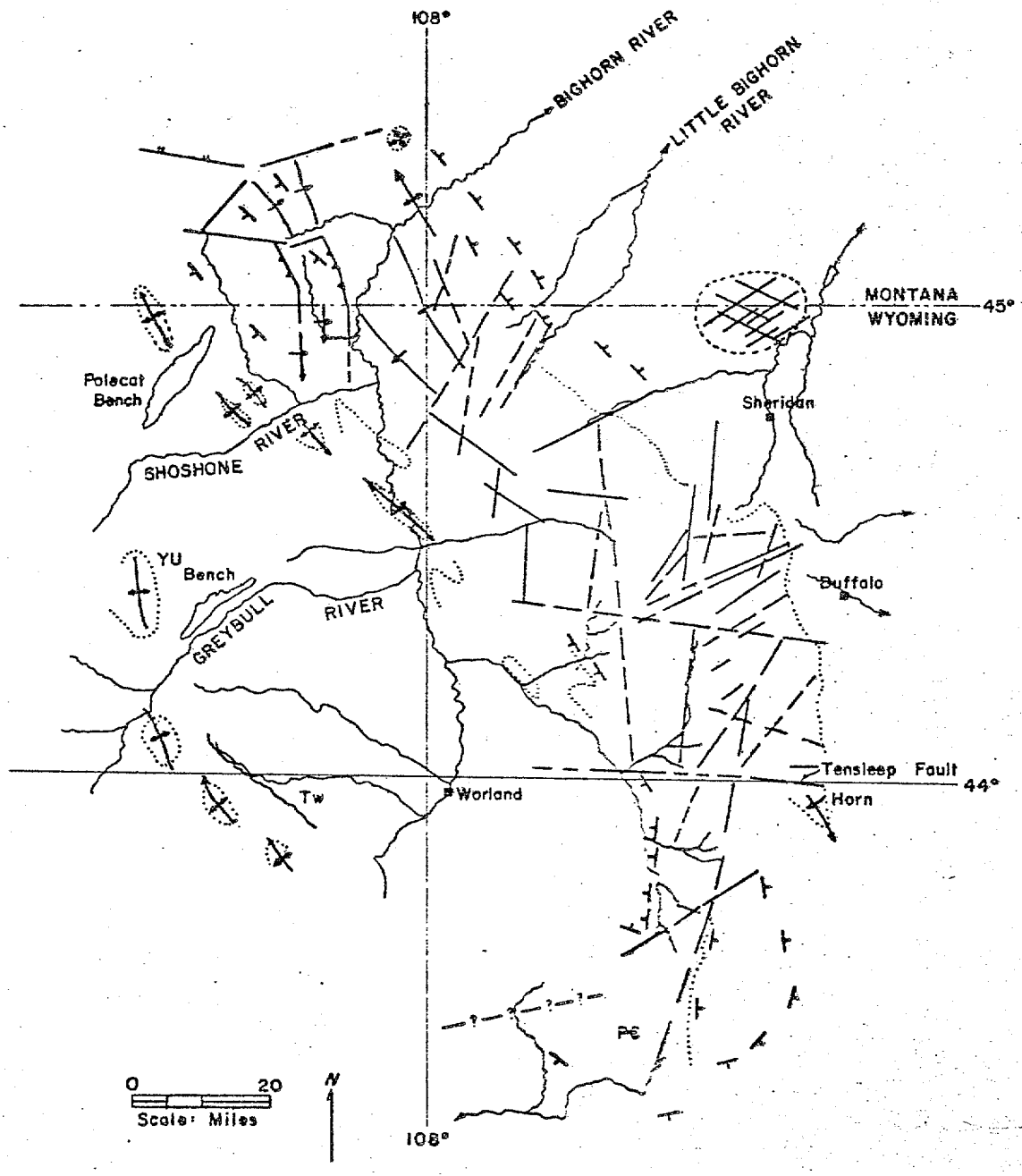

Figure 4. Major linear elements of the Pryor and Bighorn Mountains.

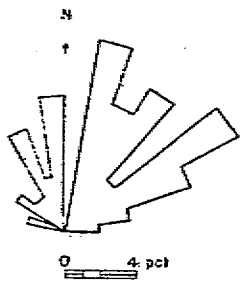

Figure 5a. Rose diagram showing trends and orientations of observed linear elements.

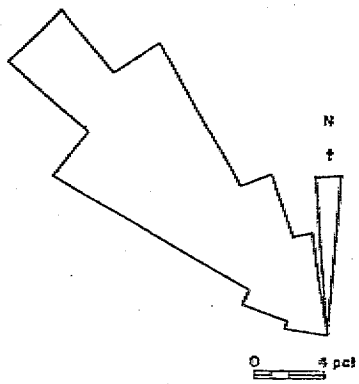

Figure 5b. Rose diagram showing the orientations of fold axis in the Bighorn Basin.

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INTERPRETATIVE TECHNIQUES IN REMOTE SENSING

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ABSTRACT: Increasing availability of remote-sensor data and improving interpretative techniques have resulted in recognition of remote sensing as a valuable tool for the geoscientist. Much can be gained from some of these data by applying traditional photointerpretive techniques, but still more can be gained if specialized interpretive techniques are selectively employed. Proper use of new interpretive techniques requires that the user have a basic understanding of the data—how it is obtained and what it represents. The user must also keep in mind the limitations of the data, such as its spectral, spatial, and brightness resolution.

With these considerations in mind, the user is ready to select the type of remote sensor data that will best apply to his problem and then tailor the processing and analysis of these data to obtain the maximum amount of information with the least expense.

The geoscientist may employ various forms of image enhancement or he may choose to use the computer in helping him make his discriminations and classifications. Some enhancement techniques are employed with visual image analysis, such as color-additive and color-subtractive viewing, stereoscopic and pseudo-stereoscopic photo interpretation. A few procedures are ordinarily accomplished through computer analysis (brightness ratioing, atmospheric correction), but others are effective with either imagery or numerical data. This latter group includes contrast stretching, density slicing, cluster analysis, pattern recognition, frequency analysis, and edge enhancement. Most procedures can be done in several ways, with the accuracy of the results and the efficiency of the operation largely dependent on the equipment used. Thus, the economics of the situation are the final consideration in the implementation of most interpretive techniques.

INTRODUCTION

Increasing availability of remotely sensed data and advancements in interpretive techniques have resulted in recognition of remote sensing as a valuable tool for the geoscientist. Earth resources satellite programs (ERTS and EREP) have been particularly effective in focusing attention on the potential of small-scale imagery. The broad coverage provided by these satellite systems is made available through the EROS Data Center in Sioux Falls, South Dakota. Anyone can now obtain photography or multispectral imagery for almost any place in the world. Available data include some high- and low-altitude aerial photography, thermal infrared imagery, radar imagery, microwave data, and a full range of multispectral imagery. The more exotic remote-sensor data are available only for a few sites.

Research into geologic applications of remote-sensor data has repeatedly demonstrated that image data has the greatest utility for most geologic studies. Non-imaging sensors can provide information for some applications, but practical considerations limit most users to analysis of photography and readily available scanner imagery. Figure 1 summarizes the spectral ranges of common imaging sensors and illustrates some of the basic distinctions.

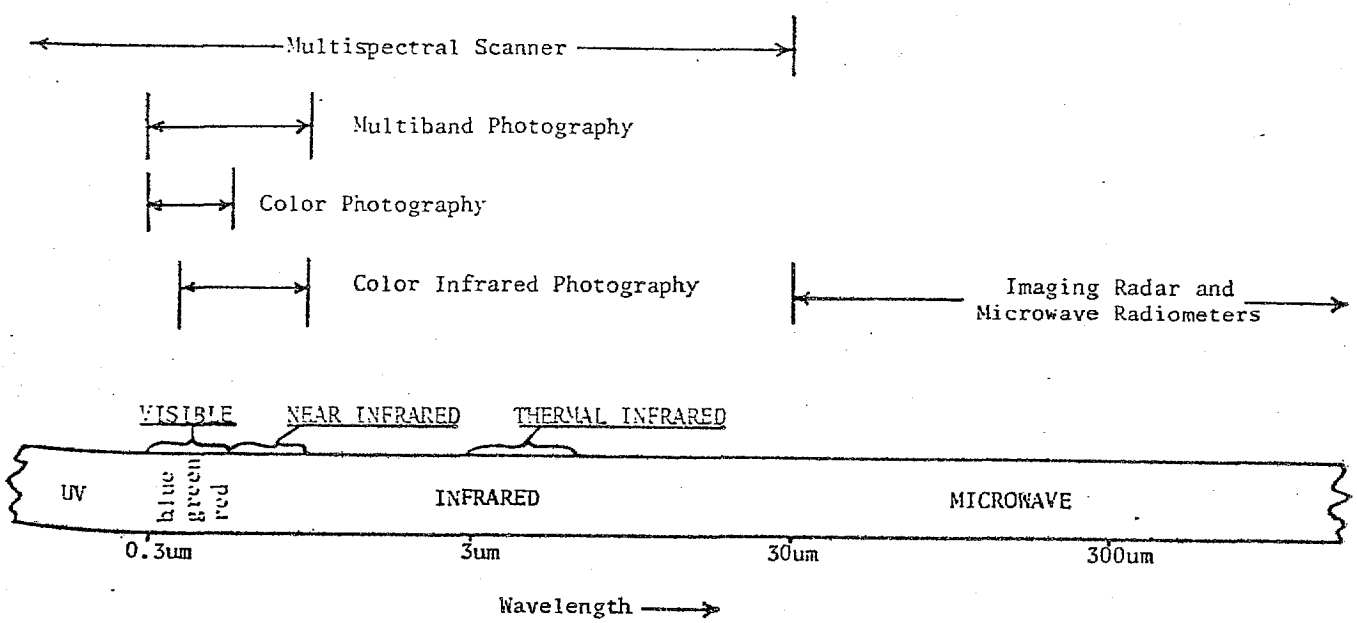

Figure 1. Spectral sensitivity ranges of imaging sensors.

IMAGE DATA

In order to understand the use of remote sensor data, one must first understand its basic characteristics — what it represents. In general, a brightness value recorded on a photograph or scanner image represents the total intensity of electromagnetic radiation entering the receiver at a particular point. This energy consists of imaging radiation received directly from the target (or scene) and non-imaging radiation that is scattered into the receiver by molecules and particulate matter in the atmosphere (Figure 2). The non-imaging radiation appears as haze and is generally detrimental to the recorded image.

A multiband camera system records separate photographs representing several spectral bands. These are generally obtained by ganged cameras each having a different film/filter combination. For example, one camera might be fitted with a Kodak Wratten filter #25 and panchromatic film so that the 600-700 nm band (red) would be recorded, while a second camera, fitted with a #87 filter and infrared film, records the 720-900 nm band (infrared). A suite of multiband photographs need not cover the entire photographic spectral range and the different "bands" may or may not overlap. The camera and film/filter configuration is commonly dictated by a particular need or preference.

A multispectral scanner receives energy through a small, moving aperature. The incoming energy is split into its various spectral components and converted into electric signals by means of photoelectric detectors. Each individual signal can then be recorded on magnetic tape or displayed immediately on a cathode ray tube. Multispectral scanners can record radiation in the visible and photographic infrared range and in spectral bands beyond the photographic range (ultraviolet through thermal infrared). Multispectral scanners generally cover a complete spectral range in discrete wavelength increments. Other configurations are possible but special requirements are commonly left to some later phase of data manipulation.

Imaging radar and microwave radiometers produce images much like a scanner image but in spectral bands well beyond the thermal range. These long-wavelength sensors employ antennae rather than optical detectors as receivers and, in the case of radar, the system produces the electromagnetic radiation that is reflected from the target.

Until recently, black-and-white photography was the only form of remotely sensed data generally available. Now, color infrared and color photography, multiband photography, and multispectral scanner imagery are widely available. Color photography is more useful than black-and-white photography because it contains hue information in addition to tonal and textural information (Carter and Stone, 1974). Multiband photography may contain all the information available from color and color infrared photography but has greater flexibility because the data are more readily manipulated. Multispectral scanner imagery is much like multiband photography but has the additional advantage that it can include spectral bands outside the photographic range.

Multiband photography and multispectral imagery may be interpreted in the same manner as a standard photograph. The image interpreter can derive most of

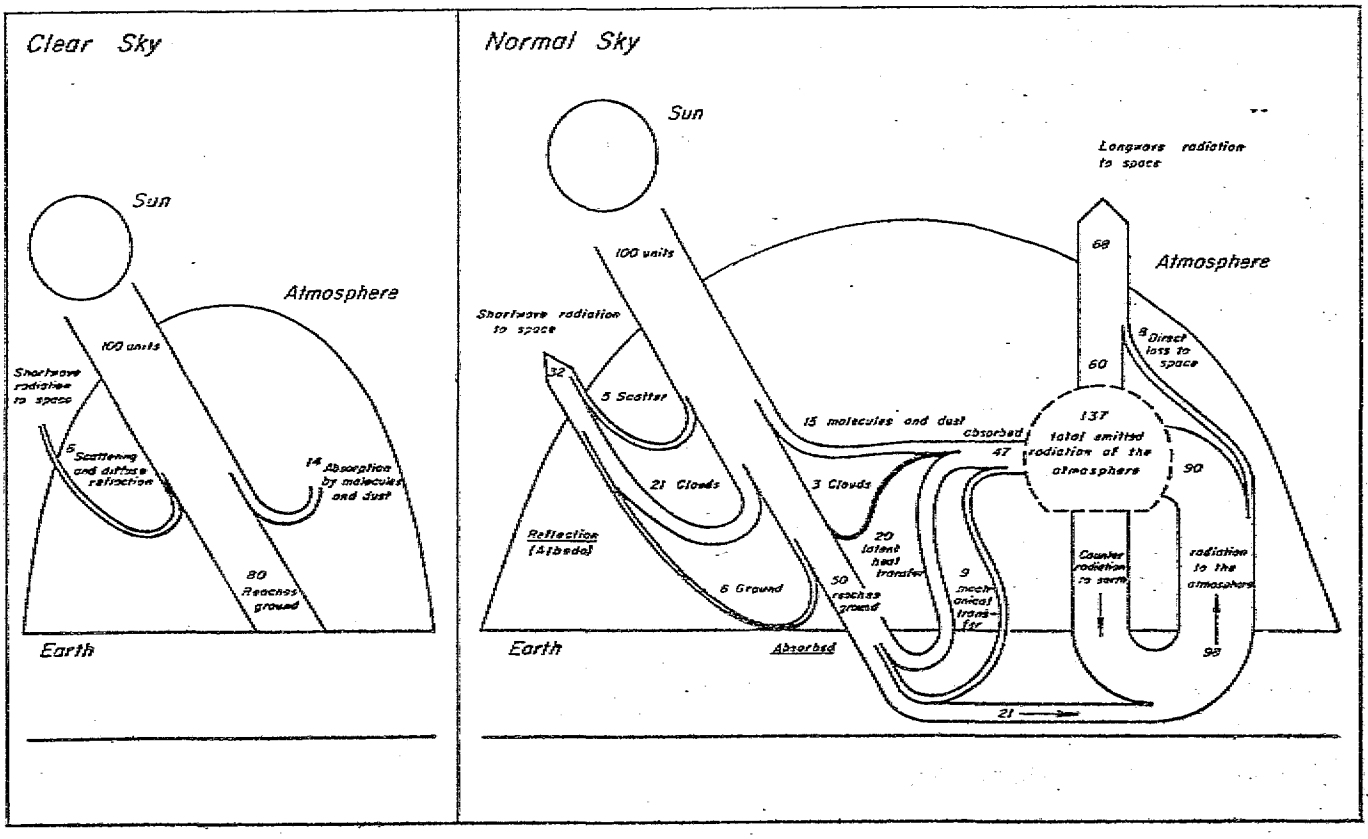

Figure 2. An energy flow diagram summarizing the energy interchange between the sun, the earth and the atmosphere (after Estes, 1974, p. 18).

the information normally available from black-and-white photography from a single band of multispectral imagery, but the interpreter who wishes to employ the additional capability of the multispectral imagery must understand both the potential and the limitations of the data and the techniques that are available to help him in his interpretations (Draeger and Carnegie, 1974).

The chief potential of multispectral imagery lies in the increased recording range and the broad range of applicable interpretive procedures. Recording a scene as a set of multiband images effectively spreads the information normally recorded on a single photograph over several photographs. This increases the effective dynamic range of the recording system so that smaller increments of scene contrast can be recorded. Recording a scene as a group of images, each representing a specific wavelength band, allows subsequent presentation of the information to be tailored to the application. The user can employ selected portions of the spectral data or combine various image bands in such a way as to enhance the significant contrasts or minimize interfering contrasts.

LIMITATIONS

Limitations of remote-sensor data are largely dictated by characteristics of the recorded radiation and target materials and by system resolution factors that reflect the combined physical limitations of the sensor system (Rosenburg, 1971). In the case of the multiband camera systems, spatial resolution is a function of altitude, scene contrast, the lens system, film, ground speed, and platform stability. Spectral resolution depends upon scene brightness, lens and filter transmission characteristics, film sensitivity and processing. Brightness resolution is dependent upon the sensitivity of the optical and recording systems and upon the ratio of imaging / non-imaging electromagnetic radiation received by the sensor. These three resolution factors combine to limit the information available from the imagery and each must be considered separately with regard to its influence and the intended use of the imagery. For most photogeologic applications, absolute brightness and spectral resolution factors are not critical so long as the relative values are accurately represented. However, the spatial resolution of the system directly affects the information detail and the image utility. When more sophisticated interpretive techniques are invoked, the importance of brightness and spectral resolution parameters increases because of the increasing reliance on subtle changes in band-to-band response.

These same resolution parameters also govern the utility of multispectral scanner imagery (Colvocoresses and McEwen, 1973) and even radar imagery. The significance of spectral and brightness resolution factors, and the need to carefully maintain quality control in data gathering and processing will become apparent in later discussions of the various interpretive procedures. Appropriate quality-control measures may involve gathering of field calibration and reference data prior to and during data gathering operations and painstaking, step-by-step control of the image processing. Again, the quality control procedures must be dictated by the intended application and economics.

A thorough discussion of all interpretive techniques used in remote-sensing is far beyond the scope of this paper. Consequently, this discussion will be limited to non-standard interpretive methods which may be employed in routine analyses. For the sake of simplicity, the interpretive methods will be discussed as they apply to common data types such as visible and near-infrared multiband photography from Skylab or ERTS multispectral scanner imagery.

INTERPRETIVE TECHNIQUES

Most standard photointerpretive techniques are readily applied to either multiband photography or multispectral imagery. One serious drawback to multispectral scanner imagery is that it does not provide the end-lap necessary to produce a true stereoscopic model. The scanner does not image an entire scene from a single vantage point as does a camera. Rather, it builds an image, line by line, as the scanner platform progresses along the flight path (Figure 3). Consequently, the interpreter must depend upon the pseudostereoscopic effect produced by viewing two different bands of a scanner image as a stereo pair or use side-lap of adjacent scanner strips to produce the parallax necessary for stereoscopic viewing (Poulton, 1972). These techniques do not form a true stereoscopic model. Instead, they form a model which appears to sink away from the observer in either direction parallel to the flight path. The model approaches a true stereoscopic model only along the scan lines which are directly beneath the interpreter's apparent vantage point and cannot be used for topographic contouring. It does allow the interpreter to estimate relative relief of adjacent features.

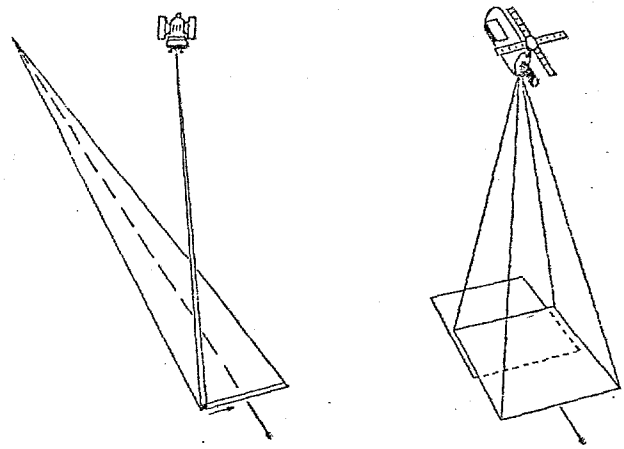

Figure 3. Diagram comparing data collection geometry of a scanner system with that of a camera.

Film transparencies are generally superior to paper prints for purposes of interpretation because they offer higher resolution and present a greater range of brightness values. They also allow greater flexibility in illumination and image combination. Transparency viewing tables are often equipped for variable-intensity illumination so that the interpreter can adjust the illumination for optimum viewing over a broad range of image densities (Figure 4). These tables can also be equipped for microscopic or stereo-microscopic image viewing — features which become particularly important when working with small-scale satellite imagery.

Other methods that are applicable to either standard photography of multispectral imagery are: density analysis, masking, contrast stretching, and edge enhancement. Techniques best suited for multiband photography and multispectral imagery include color addition, color subtraction, image ratioing, cluster analysis, pattern recognition, and frequency analysis. The latter three processes require elaborate digitizers, computer processing, and/or lasar-optical equipment.

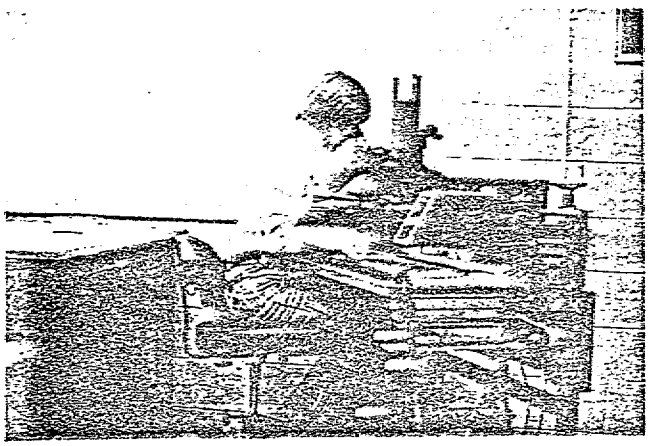

Figure 4. Stereo photointerpretation table equipped with a zoom microscope. The Richards MIM-3 split illumination table accepts one or two rolls of 10-in. aerial photography, as many as four rolls of 5-inch or 70-mm photography, and allows control of the illumination intensity. The Bausch and Lomb 240 zoom stereo-microscope provides flexibility in scale, image orientation, and film format.

Density Analysis and Contrast Stretching: "Density analysis" refers to techniques by which film densities (representing logs of scene brightness values) are accurately measured or subdivided in order to detect and delineate subtle variations in the image tone. Density analysis can be accomplished through photographic processing, photometric measurement, video processing, or digital processing. A typical density analysis procedure results in density contour map, or density slice. Density slicing can be accomplished photographically with a set of prints made with various exposures on high-contrast paper (Figure 5). The resulting high-contrast prints each represent a distinct density band (with lighter areas washed out and darker areas underexposed). Each image will be a "contrast-stretched" version of the original. The various tonal values represented within the reproduced density slice will be stretched across the entire density range of the photographic paper and the relative contrast between subtly different features should be more apparent.

A similar effect can be achieved using a digitizer and computer or a scanning microdensitometer (Figure 6a). These instruments allow the image densities to be measured and then coded or grouped according to some predetermined program. The coded data can then be redisplayed in the form of a density contour map (Figure 6b). The density contour map displays subtle film-density variations in strongly contrasting shades or colors so that the interpreter can detect and map features that are ordinarily obscure (Buckley, 1971).

Density analysis by computer is readily applied to data that is available in digital form (such as ERTS) and provides the least loss in brightness resolution for such data. Photographic or image data must be digitized before being input to a computer, so photographic processing or a scanning microdensitometer may be a more efficient means of density analysis.

Video image-analysis systems (Figure 7) offer a fourth alternative for density determinations (Schlosser, 1974). A typical video system would scan an image via a television camera and subdivide the resulting analogue signal into intensity groups. These individual groups would then be coded (assigned a specific tone or color) and redisplayed on a video monitor as a density contour map. Video systems may lack the spatial and brightness resolution of sophisticated computer systems or scanning microdensitometers, but they provide "real time" analysis capability for a relatively modest cost.

Image Masking, Image Combination, and Contrast Stretching: Masking is a procedure in which one image is superimposed on another to enhance certain image features. Probably the most commonly employed form of image masking is color-additive image composition, a technique by which false-color images are constructed from various bands of multispectral imagery (Figure 8). Color composite images can be produced electronically from digital or analogue tapes through a flying spot recording device or cathode ray tube. If the data are available in image form, other devices can be used to produce false-color composites. For example, the four bands of black-and-white ERTS imagery can be transformed into false-color image using diazo equipment (Wildeman, 1972), a color-additive viewer (Ross, 1973), a multiple-exposure printing system (Kreitzer, 1974), or video equipment.

Color-additive viewers are projector systems which allow several images to be simultaneously projected on a viewing screen (Figure 9). The black-and-white images can be filtered, brightened and scaled independently so the hue and brightness of the resulting false-color composite image can be adjusted to suit a particular need. Repetitive-exposure printing on color film or sandwiching of diazo color films provides an economical alternative to the color-additive viewing but is dependent upon the scale-stability of the recording system and may be more difficult to control with regard to the color balance and tone of the final product. Diazo sandwiching may be the least flexible color-additive technique, in that it allows no means of scale-change, but it is certainly the most economical way to construct a hard-copy, color composite image (Figure 10). Recently, the capability of experimental video equipment has been increased by addition of auxiliary equipment to allow density analysis, edge enhancement, image-calibration, and image combination (Piech and Walker, 1974). Color-addition is just one function of such analysis systems.

Color-additive systems can be employed both in positive/positive image masking (color-additive viewing) and in other forms of image masking. Positive/negative masking is accomplished by placing a negative of an image over the positive of another image of the same area for a different season (Figure 11a) or by placing a negative of one spectral band over a positive transparency of another band (Figure 11b). In either case, the image mask should

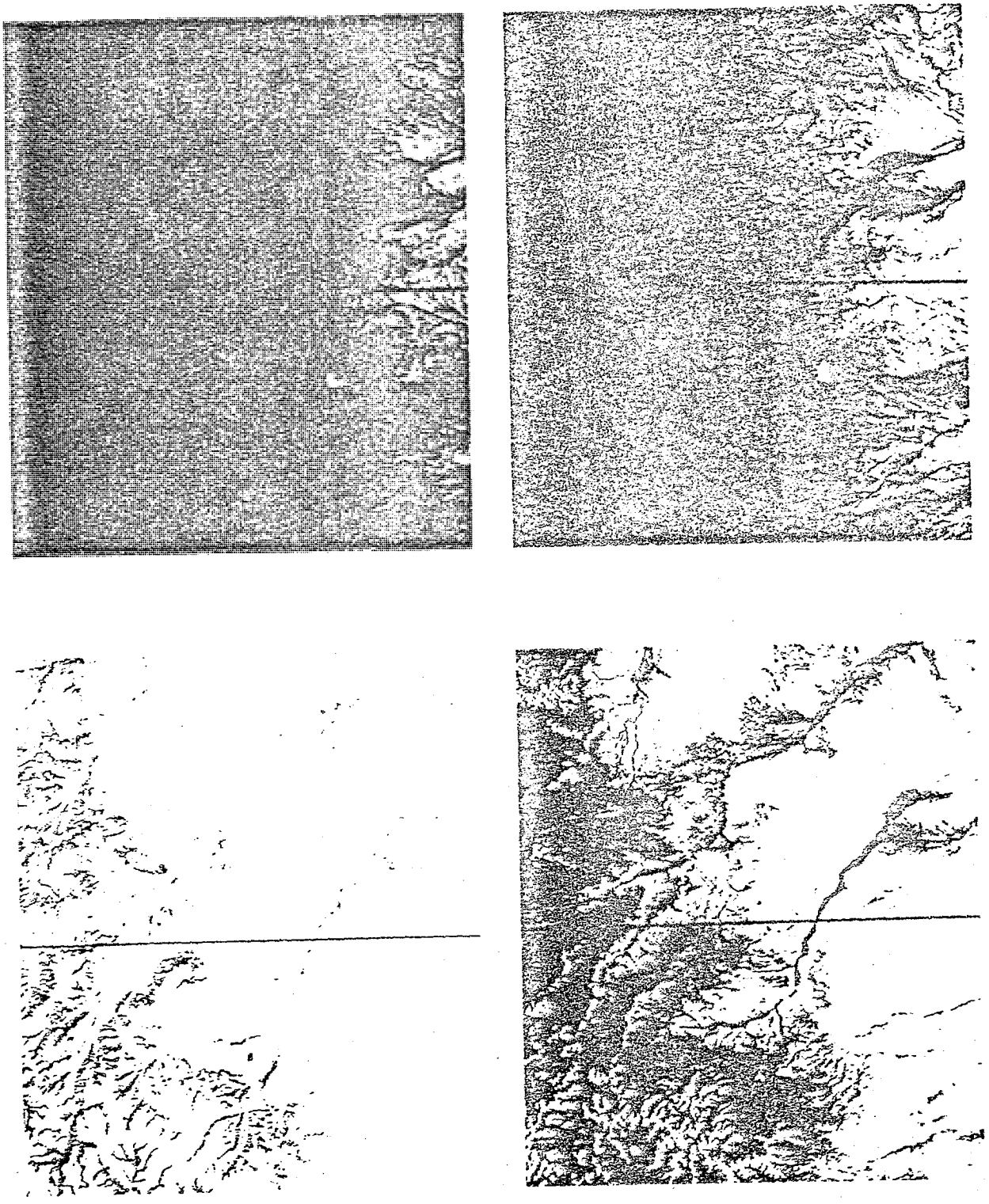

Figure 5. A series of high-contrast prints representing a set of photographically produced density slices. The density slices are from ERTS-1 image 1014-17350-5 and show the area around Cody, Wyoming.

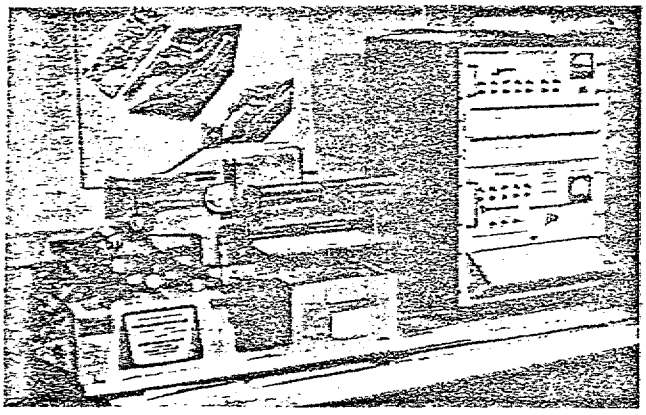

Figure 6a. A density analysis system composed of a Joyce-Loebl Mark III microdensitometer and a Tech Ops four-color isodensitracer.

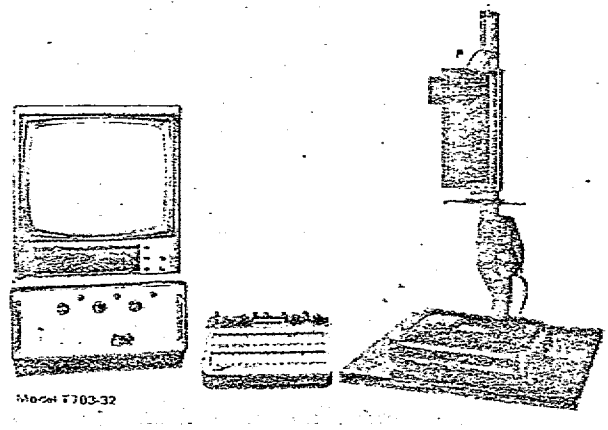

Figure 7. A video analysis system capable of real-time density analysis in 32 colors (Spatial Data Systems Model C703-32 Datacolor density analysis system).

serve to enhance differences between the images. When a positive and negative of the same image area are used the features enhanced should represent changes in contrast and overall brightness related to temporal changes in the scene while the band-to-band image mask enhances features that differ in their spectral reflectance characteristic. If the positive and negative of a single image mask are processed so that the brightness and contrast values are complimentary, the resulting composite should appear totally grey. Any variation from the reversed contrast should stand out sharply from this grey background.

A single-image mask (two positives of the same image) can also be used for edge-enhancement simply by shifting one positive slightly with respect to the other (Figure 12). Varying the direction of shift results in enhancement of different edges. The enhanced edges are those that are largely perpendicular to the direction of shift.

Innumerable image-mask combinations are possible. With proper flexibility built into the equipment used in constructing the image masks, masking techniques allow enhancement of the most subtle contrast in hue or tone. Computer processing can produce image ratios, image products, or other complex combination functions in addition to direct additive or subtractive masks. With this capability the interpreter has even more flexibility in his image enhancement procedures (Billingsley, 1973; Rowan, 1973; Goetz, 1973; and Vincent, 1973). The interpreter may selectively remove unwanted image contrasts and increase residual contrasts which may be more "meaningful" in a particular application. Feature detection is limited only by the image resolution and proper selection of spectral bands.

Edge Enhancement: Edge-enhancement procedures aid the interpreter in defining trends and area boundaries. Techniques for producing edge enhancement are many. Density slicing can be used as a form of edge enhancement if the individual image density values included in a coded group are restricted to very

Figure 6b. A density contour map of Yellowstone Lake and a portion of the Absaroka Range. This density contour map was produced from ERTS-1 image 1015-17404-5 using a Joyce-Loebl Tech Ops four-color isodensitracer (figure 6a).

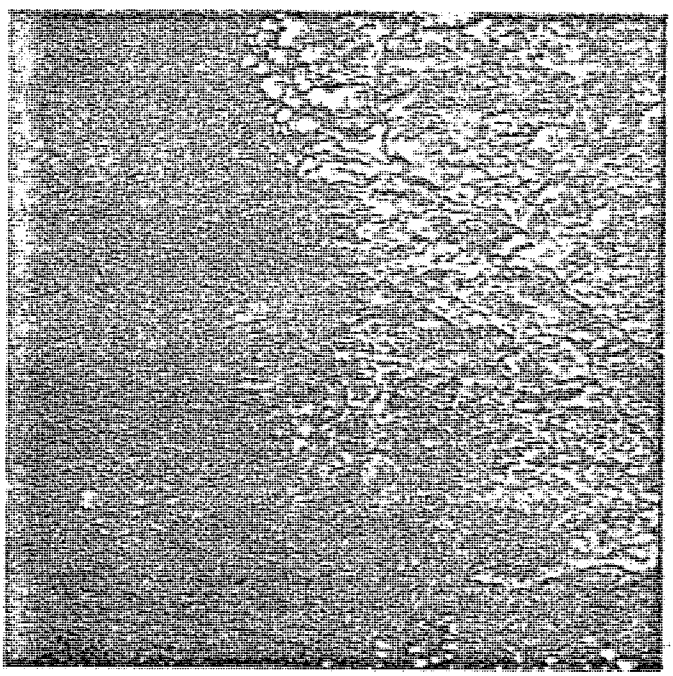

Figure 8. A false-color composite image of the Wyoming Thrust Belt and Green River Basin composed of four diazo film transparencies of ERTS-1 image 1374-17360.

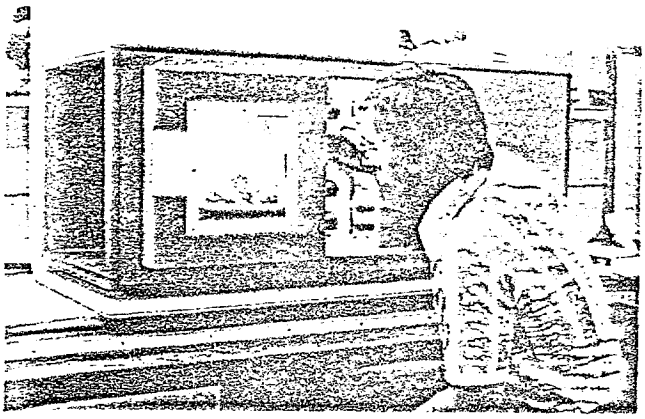

Figure 9. A spectral Data model PV-62 color-additive projector viewer used to construct false-color composite images and display image masks from multiband photography or multispectral imagery.

narrow limits. The coded density values then produce a line, or series of density contours, corresponding to any significant contrast change or "edge".

Digital or analogue image analysis systems may produce edge enhancement by sampling consecutive data points and displaying the resulting density curves or by determining whether or not the rate-or-change of brightness values exceeds a threshold value (Figure 13). Those values where the brightness change is sufficient to exceed the threshold may then be re-displayed in the form of an edge-enhanced image. This is, of course, the same principal as is used in a simple density-slice edge enhancement. As mentioned previously, one of the simplest and most effective methods of edge enhancement is to form a positive/negative mask of an image in which the two images are slightly mis-registered. Mis-registration allows excess amounts of light to pass through the image mask along the edges of highly contrasting objects. By shifting the superimposed image in all directions relative to one another edges of all orientations can be observed.

These edge enhancement procedures help the interpreter to define area boundaries regardless of the shape or orientation of the contrast changes defined as edges. Other edge enhancement procedures can help an interpreter define only trends or linear anomalies on an image.

One such technique consists of superimposing pattern grids on an image in various orientations. The interference patterns formed between the image and the pattern grid may cause linear and/or curvilinear features to stand out strongly as they become coincident with the grid patterns.

A somewhat more sophisticated form of edge enhancement can be accomplished through frequency filtering using an optical bench. In this process, the image is illuminated with coherent light (laser), and the resulting transmitted beam, which has been altered by its passage through the image, is made to interfere with a reference beam. The resulting interference pattern represents a frequency transform of the original image. Selective filtering of the transform image, by blocking or masking selected elements, can remove unwanted elements of the photograph (Pincus, 1969). An edge enhanced or other special purpose image can then be reconstructed by a reverse optical process.

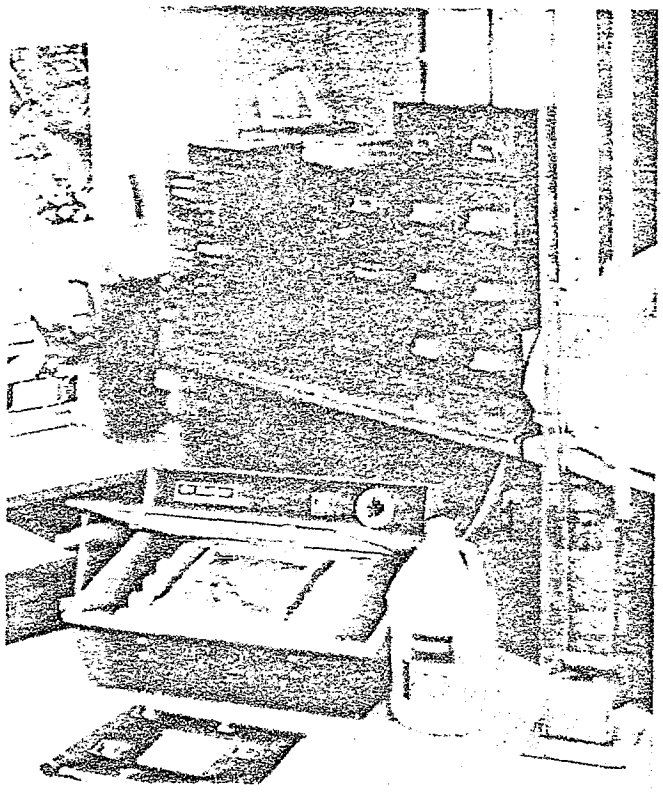

Figure 10. Apparatus used in the construction of diazo color composites. This system consists of a light box and timer (Bruning Varityper 50) and an ammonia developing tube (Bruning model 05-748).

Clustering, Pattern Recognition, and Frequency Analysis: The digital computer provides capability for automated mapping of features that are strongly expressed on the multispectral imagery. Selection criteria programmed into the computer can vary from single image density analysis to extremely complex functions (Simonett, 1974). Useful functions commonly take the general form of three basic styles of classification: clustering, pattern recognition, or frequency analysis.

Clustering is a procedure in which band-to-band comparisons are made for individual image points or sets of points. Each point is assigned a position in an array on the basis of the relative response recorded on the various bands of multispectral imagery. All points with identical or similar response on each spectral band will fall into a single group or "cluster". When all image elements have been assigned the clusters can be coded and printed in the form of a computer map (Smedes and others, 1971). The map may represent a finished classification or may be used as an aid in image interpretation. Different cluster maps can be produced by changing the boundary selection criteria for the clusters or by using different sets of image bands.

Some procedures use both the relative band-to-band response of data points and rates-of-change of brightness values as selection criteria (Centner and Hietanen, 1971). Consequently, maps produced through these analysis can represent both spectral and spatial relationships of the original data. The general procedure is much the same as in cluster analysis except

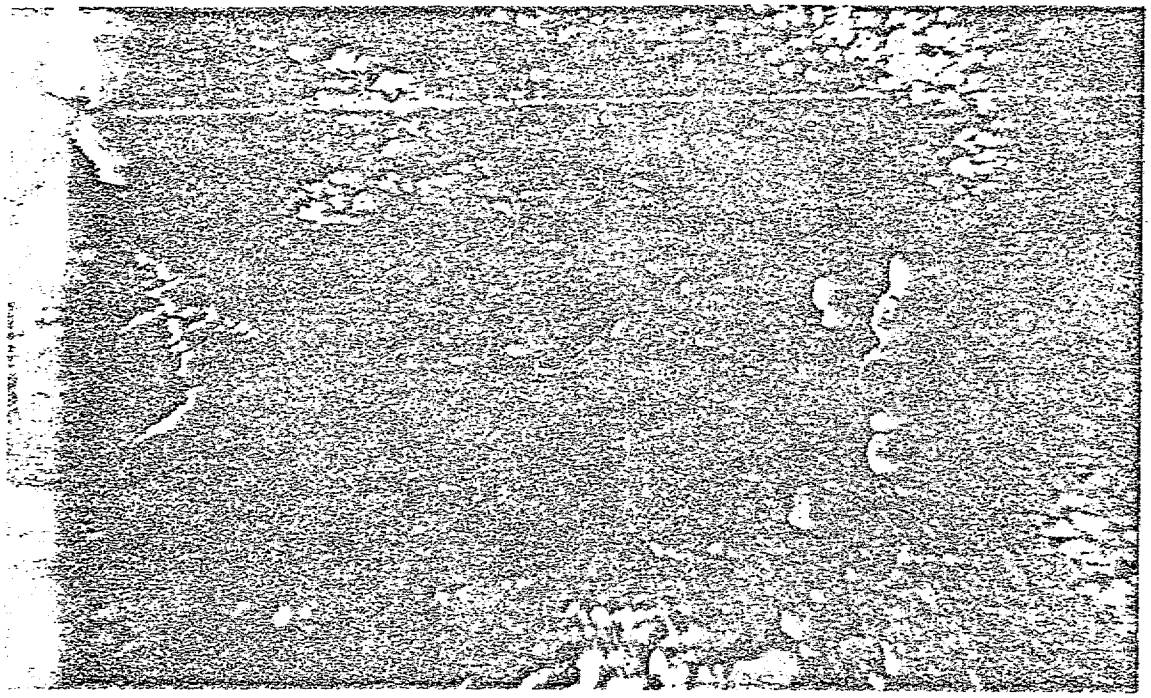

Figure 11a. A season-to-season positive/negative mask of the Laramie Basin composed of a band 6 positive of ERTS image 1029-17184 (August 21, 1972) and a band 7 negative of ERTS image 1353-17190 (July 11, 1973). This image mask enhances differences in surface water distribution, clouds, and vegetation.

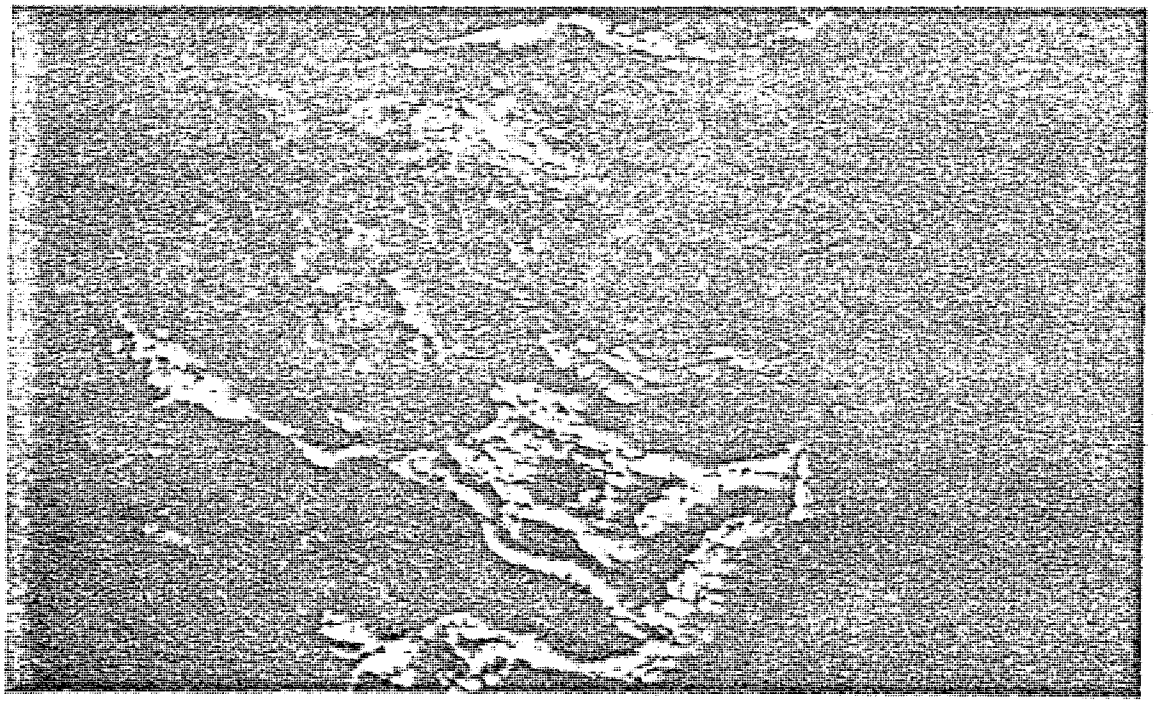

Figure 11b. A band-to-band positive/negative image mask constructed from a negative band 5 and a positive band 7 of ERTS image 1373-17295. This image mask emphasizes spectral differences between vegetation and rock outcrops in the Wind River Basin.

Figure 12. A single-image mask of the Wind River Mountains and northern Green River Basin showing edge enhancement (or linear feature enhancement) produced by mis-registration of the two images. A positive band 5 and band 7 or ERTS image 1068-17353 (September 29, 1972) comprise this image mask.

that the groupings take into consideration the value of each point relative to its neighboring points, as well as similarity of response in each spectral band.

Frequency analysis is a further modification of procedures which employ the spatial relationships of the data in classification (Hornung and Smith, 1973). The relationship of each point is considered with respect to many of its neighbors. Both rates-of-change of brightness values and repetitive aspects of these brightness changes are considered. Fourier analysis of image values is a frequency analysis procedure comparable to the optical bench procedures described under "edge enhancement". Both techniques can be used to enhance particular features by increasing certain frequency components relative to others.

Computer classification schemes can be used for automated mapping or as aids to the interpreter in making objective decisions. In general, only features that are displayed in regular and predictable relationships to one another (such as crops, buildings, trees, etc.) are amenable to automatic classification. The geologist must often make decisions on the basis of characteristics of a particular data point, its relationship to other points, and its context, while ignoring certain image elements which he considers noise. These combined decision criteria are generally too complex and variable to be programmed, consequently a geologist's use of computer classification procedures seldom goes beyond applications where the computer seves as an aid in making objective decisions or as a means of preliminary analysis to define general areas of interest.

SUMMARY

Remote sensing is a tool which offers the geologist an efficient approach to solution of many problems. In order to realize the full potential of this new tool the geologist must understand and employ some rather specialized interpretive techniques. Fortunately, many

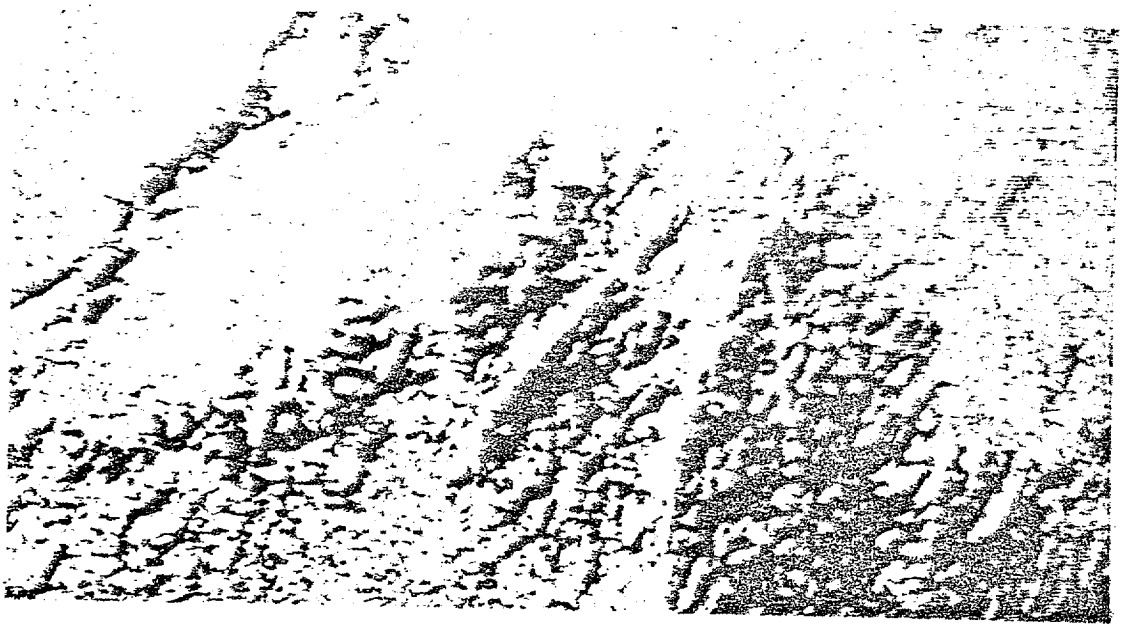

Figure 13. A video edge enhancement of a portion of the northern Laramie Range. This enhancement was done from band 5 of ERTS image 1047-17132 (September 8, 1972).

of the most useful techniques can be accomplished in several ways. Some methods are quite expensive and require special equipment while others can be accomplished for a very modest investment and employ equipment that is widely available. The cost of a procedure generally reflects the speed or flexibility of the analysis rather than the quality or utility of the analysis.

Certainly, then, the interpretative procedures employed and the equipment used must be governed by need and economics. The data user must know the analysis alternatives that are available to him in order to select those that will give him the most return for his investment.

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GEOLOGIC INTERPRETATIONS OF ERTS-I IMAGERY, BIGHORN MOUNTAINS

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ABSTRACT: ERTS-1 imagery provides a superb regional view which confirms the complex nature of the Bighorn uplift. Many structures can be correlated with known features. Others can be extended beyond their presently mapped limits and some separated features, such as the Badwater-Big Trails faults, can be connected. Linears are mainly confined to the uplift. Most linears are topographically expressed, with the rest being marked by tonal contrasts. Many linears can be related to faults or fracture zones, but others occur along drainages with no bedrock exposed. Linear plots of ERTS imagery, aerial photography, and fracture diagrams all show the dominant trends to be N. to N.20° E, NE, and E-W. The strong northwest trend of anticlines and monoclines and of ground-measured fractures is subdued on the ERTS imagery owing to the southeast sun azimuth.

Mapping of lithologies is less satisfactory and can be done only in a general way. Remote sensing unit contacts seldom correspond to stratigraphic contacts. Nevertheless the patterns are helpful in outlining many folds.

INTRODUCTION

The Bighorn Mountains comprise a portion of an ERTS-1 project covering much of northern Wyoming (103°-110°W, 43°-46°N). The objectives of this project were the delineation of lineaments, the outlining of possible large blocks within the uplifts, and determining the degree to which folds, faults, and other geologic features could be discerned. The problem of the large lineaments is covered elsewhere (Hoppin, 1974).

This paper will be restricted to a consideration of some specific areas that were field checked during the summer of 1973 (Fig. 1). Areas 1, 2, and 4 are summarized here. Area 3 is covered in the accompanying paper by Swenson. For further details, the reader is referred to the complete MS theses and NASA progress reports.

The procedures followed by each investigator were essentially the same. The imagery was first examined and annotated. Excellent fall and winter scenes were utilized. Both positive and negative prints enlarged up as high as 1:250,000 were made. 70 mm. transparencies were analyzed in I²S Addicol and Digicol viewers. Most useful was a fine color composite prepared by NASA Goddard Space Center. High altitude black and white photography (1:58,000) was available for the entire region. In addition two east-west U-2 flights, one across area 2 and the other across area 3, consisting of 70 mm. multiband photography and 9x9 color infrared photography (1:125,000) were flown by NASA. A part of area 4 was covered by an east-west flight by the Colorado State University aircraft with I²S multiband and color infrared (1:854,000) cameras. The initial analysis of satellite and aircraft imagery was followed by comparison with published work in the area and this, in turn, supplemented by field checking. Stereo viewing of the 30 per cent sidelap was very helpful.

NORTHWEST BIGHORNS

Area 1 outlines the primarily structural study by Voldseth (1973). Two enlarged scenes are presented, one in fall (Fig. 2) and one in winter (Fig. 3) to illustrate the contrasting, complementary character. Note particularly the enhancement of topography in the areas of relatively low relief as a result of the combination of optimum snow cover and depth, and low sun angle. On the other hand areas of high relief show up better on the fall imagery. The salients and reentrants of the northwest flank are strikingly revealed. This pattern is a result of two sets of monoclines and faults, one northwest and the other N. 10° E. in trend. The complex Tongue River lineament marks a sharp discordancy across the uplift but is not at all evident in the basins. Precambrian rocks can be distinguished from Paleozoic rocks only in a general way; the smaller, irregular occurrences of gneiss north of the Tongue River lineament cannot be distinguished. The previously unmapped large slide was first observed on conventional photography but can now be readily seen in Figure 2. A bench capped by flat lying Embar formation can be accurately outlined. A number of straight drainage segments, probably fracture controlled, are present (south of Shell Canyon). The marginal upthrusts cannot be identified as such, and can only be placed on the basis of ground truth.

CENTRAL BIGHORNS

Area 2 was studied by Manley (1974). Of particular interest were the strong topographic linears in the central core of the range. The east-west linear is the Florence Pass lineament. The north-south glaciated west Tensleep Valley appears to extend to the north across the crest of the range. The northeast linear was noted first on the ERTS imagery and was named the Kearney Creek linear. Shortly after the first imagery annotation was done, the publication of Kiilsgaard, et al. (1972), appeared which provided a valuable new source of ground truth. The Kearney Creek linear was found to follow a major Precambrian fault zone.

Figure 4 is an enlargement of a portion of figure 1. Figure 5 is a linear overlay of Cloud Peak Primitive area which includes both visible linears and mapped but not visible faults. (A comprehensive linear classification map is Plate 1 in Manley, 1974). Figure 6 is a reproduction of a map from Kiilsgaard, et al. (1972), reduced to the same scale as figure 4. Matching points are marked by the circled dots.

Some linears can be related to known faults or can be found upon field checking to follow fracture or shear zones. In many instances, however, topographic linears follow valleys in which there is no bedrock exposed owing to heavy forest cover, talus accumulation, or glacial deposits.

The nearly north-south feature annotated in Figure 4 was at first thought to continue through the crest of the range and provided the initial reason for working in

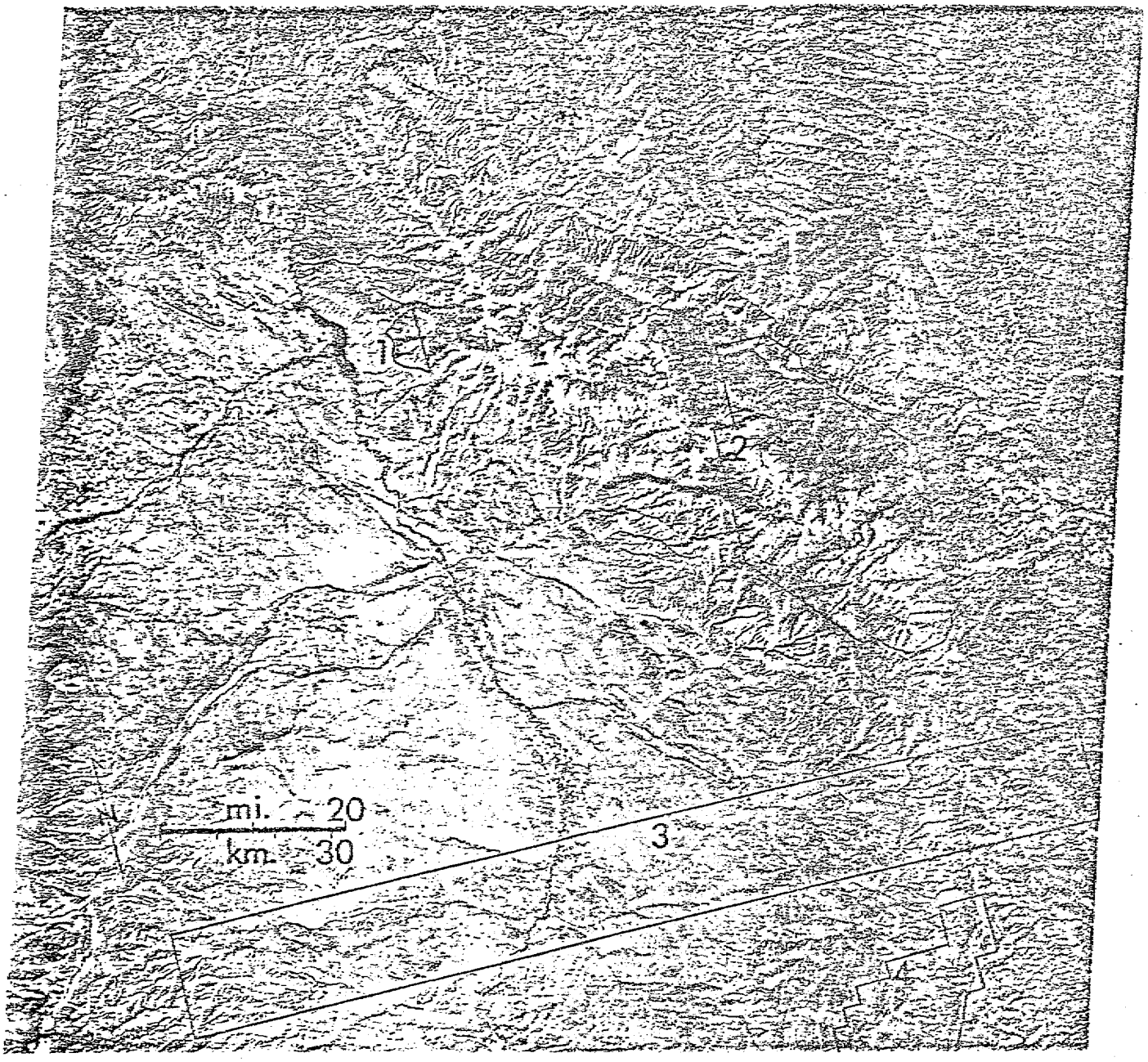


Figure 1. -ERTS MSS band 7 scene (fall) of Bighorn region 1-4. Areas studied in summer 1973.

this area. The U. S. Geological Survey study maps a fault northward from the Kearney Creek linear (although this is the only fault mapped along the length of the north-south feature). This fault coincides with an ERTS linear through the Bighorn Reservoir. The continuation of the linear into a valley with glacial deposits suggests the fault, too, continues for a distance to the north. Between the Kearney Creek and Florence Pass linears the north-south feature is not obvious although it is easy to imagine a continuation on the basis of the linearity north and south of this section. Although this area was closely examined on high altitude photographs and was observed from a light plane, no evidence of a structurally disturbed zone was found. South of the Florence Pass Lineament the linear is expressed as the glaciated valley of West Tensleep Creek. A small deflection of the magnetic pattern (Figure 6) is evident along the creek although this is possibly due to topographic relief. Between West Tensleep Lake and Mistymoon Lake no evidence of a north-south fault or fracture zone was observed in the field. Although considerable augen gneiss was found in this region, the dominant metamorphic grain of the rock was northeastward rather than north-south. This trend is also evident on the high altitude photos and is expressed on the ERTS imagery by numerous parallel glaciated valleys along the eastern side of West Tensleep Creek. Further work is necessary to determine the origin of the West Tensleep Valley.

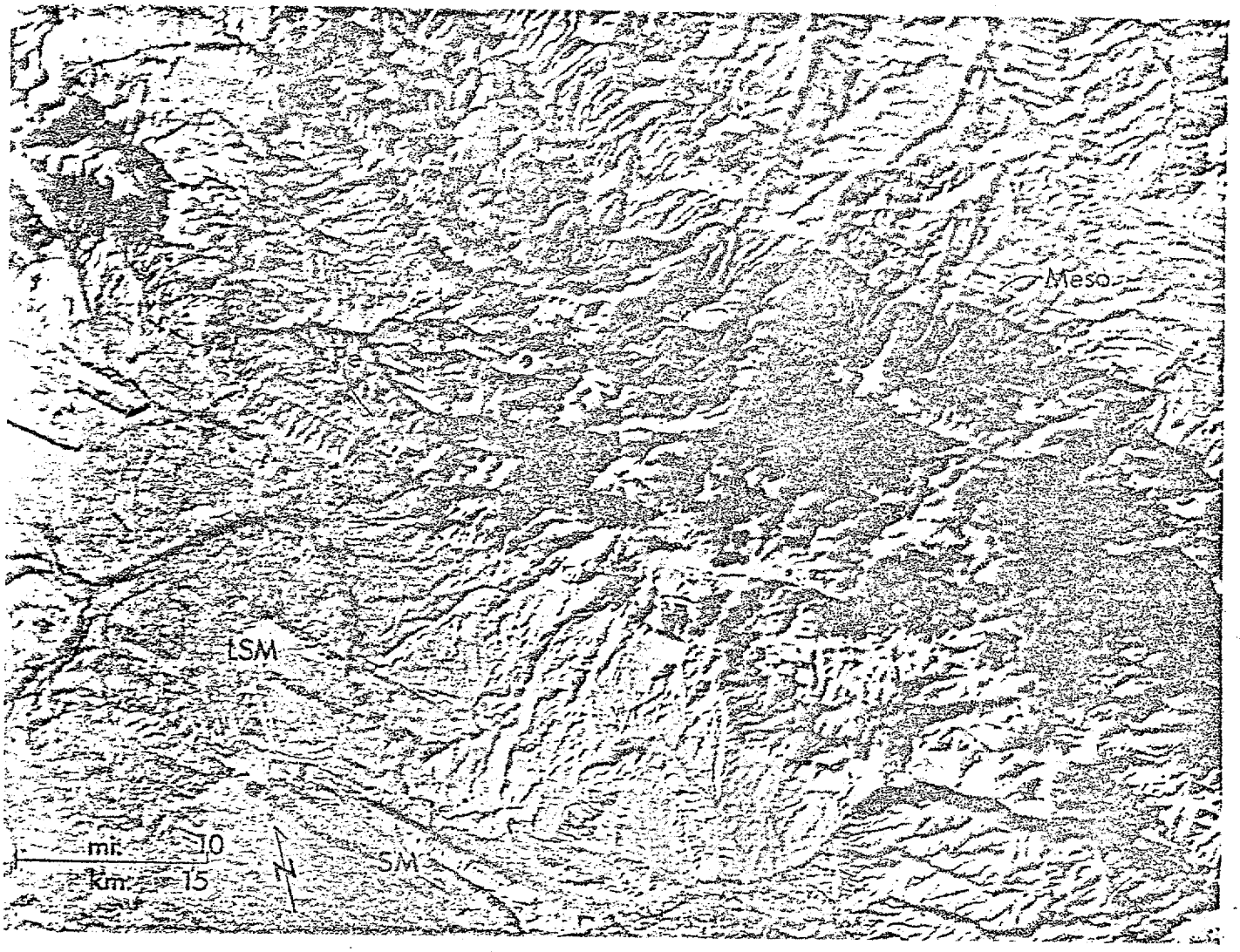


Figure 2. -Northwest Bighorns, winter scene MSS 7.
Pe -Embar formation
Meso-Resistant Mesozoic units
LSM -Little Sheep Mountain anticline
SM -Sheep Mountain anticline

Excellent exposures along several fracture controlled linears show intense shearing, brecciation and gange along with greenschist facies retrograde metamorphism.

Magnetic intensity information for the Primitive Area (Figure 6) suggests that the Kearney Creek linear may represent a major structural discontinuity in the Precambrian basement (Kiilsgaard et al., 1972, p. C30). North of this zone of faulting and fracturing the magnetic pattern has a smooth westerly increasing gradient of about 50 gammas per mile. Southward, the magnetic pattern is much more complex with magnetic highs concentrated in the high peaks region. Depth calculations show that in the northern, dominantly "granitic rocks" the magnetic pattern reflects a deepseated source and only locally reflects the "granite." To the south, however, in the dominantly gneissic rocks the sources of the magnetic anomalies are placed at or within several thousand feet of the surface (Kiilsgaard et al., 1972, pp. C30-C31).

Examination of the ERTS image in Figure 4 shows a marked difference in topography between the two areas. In addition the orientation, magnitude and number of linears appears somewhat different across the boundary. For this reason the linears were plotted on Rose diagrams (Fig. 7) for approximately equal areas north and south of the Kearney Creek linear. Slightly curvilinear features were included by taking an average reading but highly curvilinear features were eliminated. Only features observable on the ERTS image are included, and many of these were not field checked.

The results of this procedure show no radical difference between the two areas, although south of the Kearney Creek linear the frequency (Fig. 7A) and tightness of the grouping are increased. Figure 7B takes into account lengths of the linears in order to evaluate the suggestions of McKinstry (1953), Moody & Hill (1956), Price (1966) and Badgley (1965) that there is possibly a theoretical basis for linking linears through

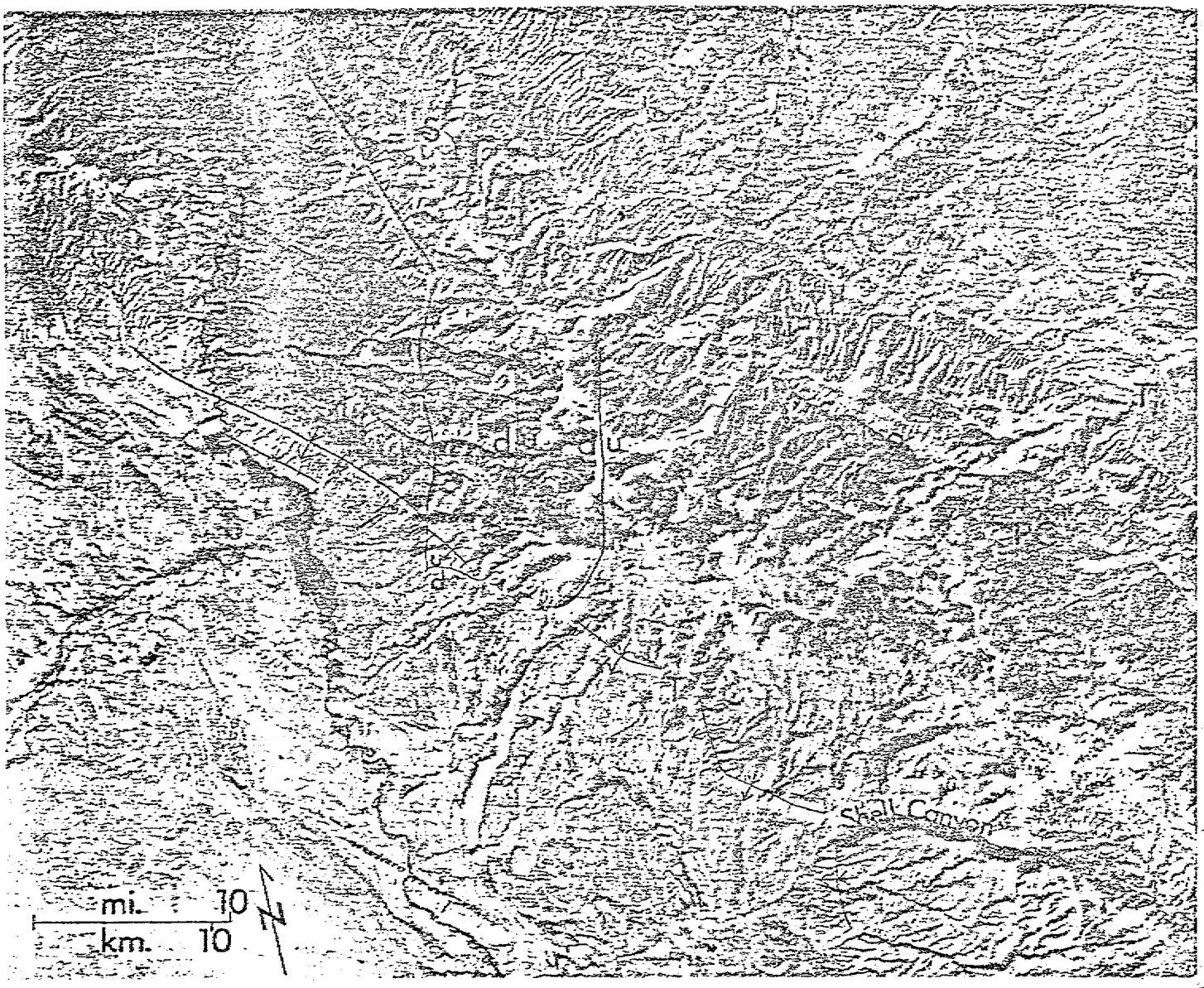


Figure 3. -Same area as Fig. 2, fall scene, MSS 7, showing main monoclines and faults (dashed thrust symbol is location of upthrusts).
S -Slide Area
T-T-Tongue River lineament (note contrast between Paleozoic and Precambrian terrains).

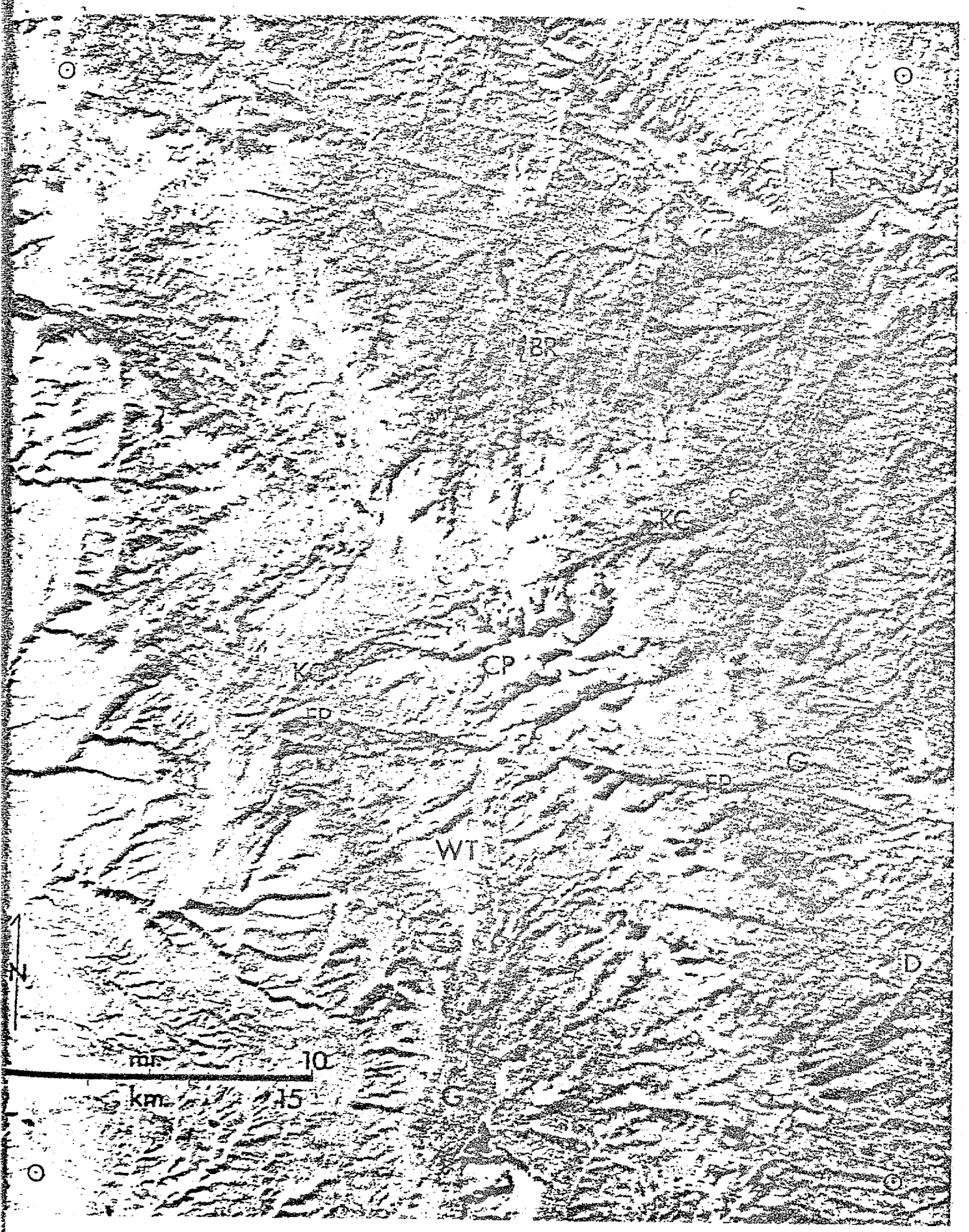
scale. Although minor variations are evident between the diagram based on length and the one based on frequency no radical variation exists.

Since the ERTS linear study is not conclusive, the major supporting evidence that the Kearney Creek linear is a block boundary rests with the magnetic data, the difference in rock types, the variation of the topography and the magnitude of the feature itself. Airphoto examination of the linear shows a zone approximately 0.5 mile wide of intense fracturing. A plot of these fractures on a rose diagram (Figure 7C) allows the larger scale fracture pattern to be compared with the pattern observed on the ERTS imagery. North of the linear, the fracture frequency diagram is fairly uniform whereas south of the linear a frequency high is noted between N70 and N75 degrees E. This varies 10 to 20 degrees from the frequency highs noted on the ERTS imagery but only approximately 4 degrees from the strike of the Kearney Creek linear itself. This suggests local control of the fracture frequency high rather than a direct relation to the larger ERTS linear pattern. Further fracture studies, particularly at the

Figure 4.

-Enlarged portion of figure 1, Central Bighorns

G	Glacial moraines
T	Tear fault at north end of Piney Creek thrust
BR	Bighorn reservoir
KC-KC	Kearney Creek linear
FP-FP	Florence Pass lineament
CP	Cloud Peak
WT	West Tensleep Valley
D	dike
0	match points for figures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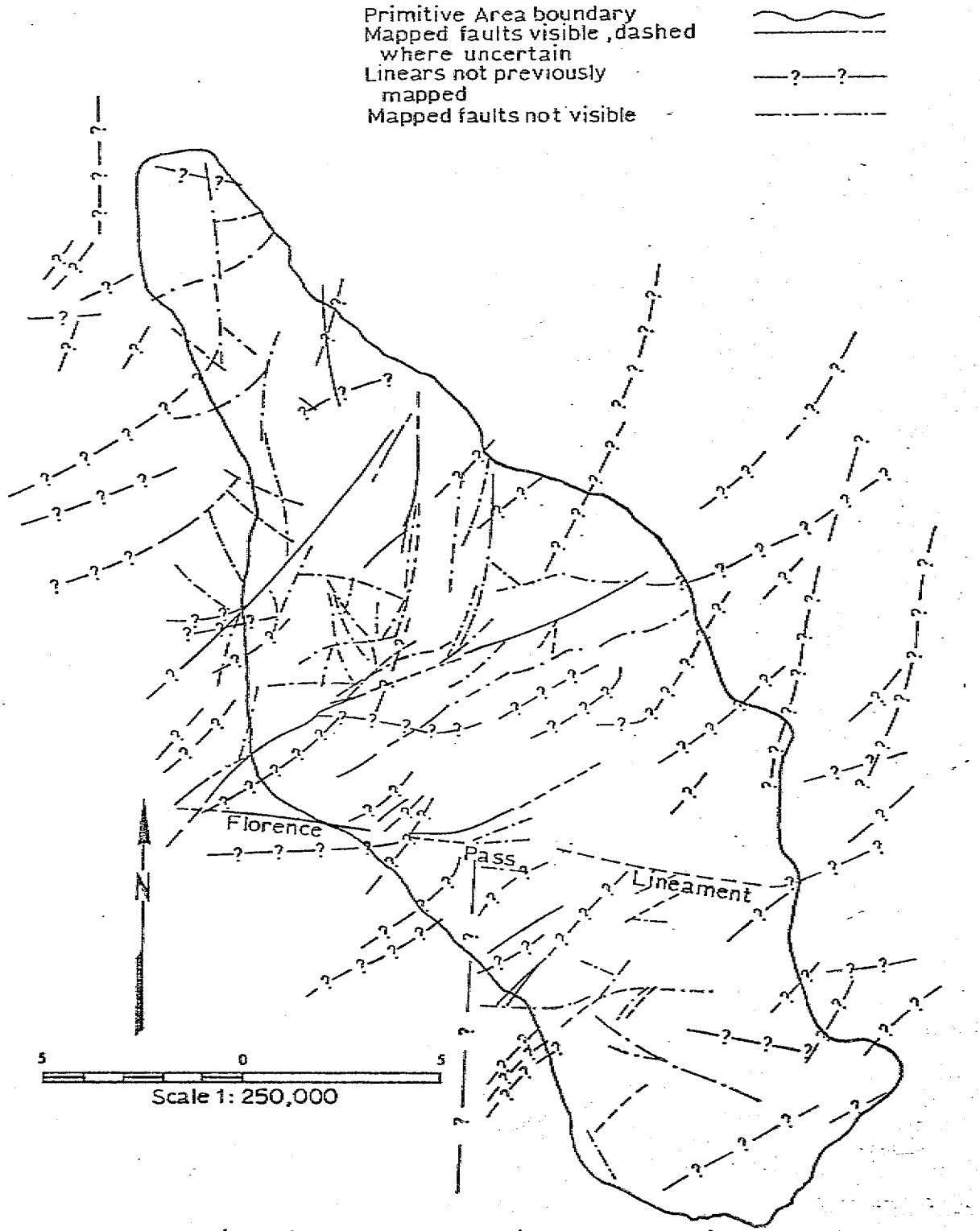
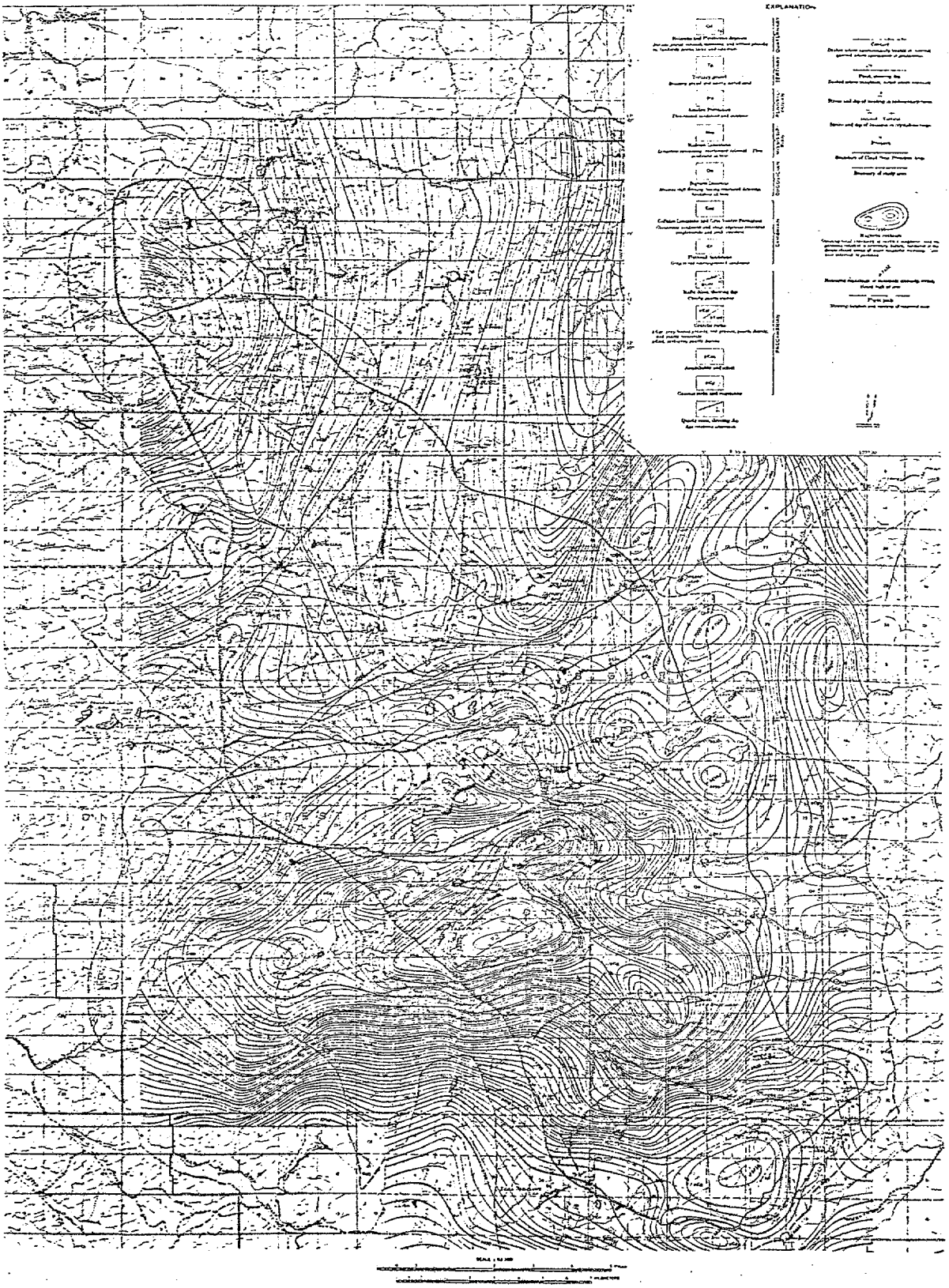


Comparison of ERTS -1 Imagery With Known Geologic Information
Cloud Peak Primitive Area , Wyoming

Figure 5. -) Comparison of ERTS-1 imagery. . . .
) Captions on figures



GENERALIZED GEOLOGIC AND MAGNETIC INTENSITY MAP OF THE CLOUD PEAK PRIMITIVE AREA AND VICINITY, WYOMING

Figure 6. -) Generalized Geologic and . . . .

outcrop level, need to be done to determine if this relation holds.

There is a higher number of northwest trending fractures on high altitude aerial photographs (Fig. 7C) in comparison with the number of northwest trending ERTS linears (Fig. 7A). This is partially due to sun shadow effects resulting from the southeast look direction.

No evidence for the presence of either the Cross Creek lineament (Demorest, 1941) or the Shell Creek lineament (Hoppin and Jennings, 1971) can be found on the ERTS imagery, conventional photography, or ground studies. Both included the offset at the north end of the Piney Creek Thrust. This offset is only a tear fault of restricted extent.

Several authors including Demorest (1941), Hodgson (1965), and Starmer & Koucky (1970) have discussed the Bighorn Mountains in terms of blocks bounded by faults and fracture zones. Since Demorest's tripartite division of the range, considerable structural complexity has been found. Starmer & Koucky (1970) suggest that while the range as a whole was undergoing uplift as large blocks, portions of these blocks were in turn being fractured and uplifted as "subsidiary blocks." This is suggested by the pattern of linears found north of but not south of the Kearney Creek linear. This adds further support to the conjecture that the Kearney Creek linear is a major block boundary.

Hodgson (1965) describes the Florence Pass lineament as a zone of adjustment between major basement blocks. The magnitude of the feature, as noted on the imagery, along with the strong fracture pattern visible on the high altitude photography support this. The lineament is not, however, continuous to the eastern flank of the range nor does it separate areas of differing magnetic, topographic and structural patterns. Extension to the west across the flank of the range as proposed by Hodgson (1965) is only slightly suggested by the imagery. The Kearney Creek linear is restricted to the crystalline core.

Dikes are not detectable on the imagery even in areas of essentially bare rock whereas the larger ones are readily visible on conventional aerial photography. Only a few tonal linears were found to correspond to mapped dikes and these were due to vegetational contrasts.

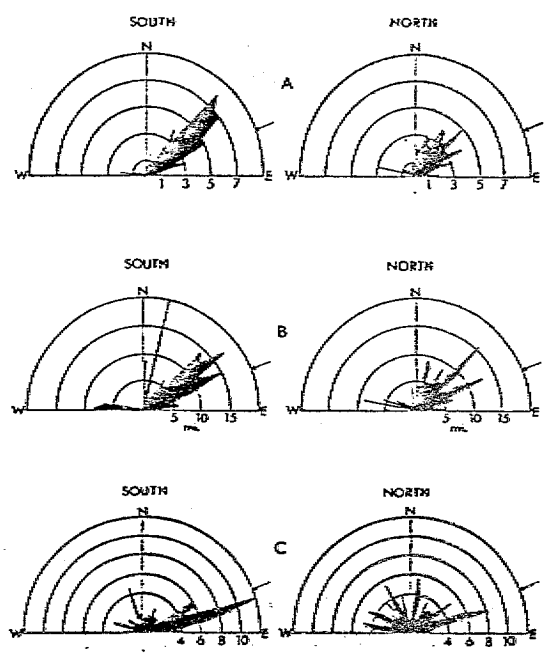


Figure 7. -Rose diagrams of linears, Cloud Peak primitive area
A. ERTS linears (on basis of numbers)
B. ERTS linears (on basis of length)
C. Linears on high altitude photographs (on basis of numbers)
Arrow is trend of Kearney Creek linear.

SOUTHERN BIGHORNS

Interest in area 4 originated with the observation of a prominent northeast trending linear which intersects the Big Trails fault (Fig. 8). A map of the area compiled from previous work, field checking and imagery analysis is in Tappmeyer (1974, Plate 1).

Figure 8 is a portion of an ERTS scene taken in May 1973. Although it doesn't provide as much detail as winter and fall scenes for some portions, it does happen to provide the best delineations of units and structure in the area to the southeast of the Bighorns. The Tisdale anticline shows up well with its core of Cretaceous Mowry-Thermopolis formations and belts of younger Cretaceous units. The outermost dipping unit is the Paleocene Fort Union formation. The northeast corner is flat-lying Eocene Wasatch formation with the small area of Table Mountain capped by Oligocene White River formation. The light tones south of the Horn and along the southeast flank of the range are mainly Triassic Chugwater formation. (Red beds show up best on high quality 9 x 9 color composite transparencies). In the northwest part of the photograph the light toned Eocene Willwood formation markedly stands out where it is in contact with Upper Cretaceous and Paleocene units. The light snow in the high areas enhances the drainage and reveals some subtle linears which may be faults (2-2, 3-3, Fig. 8).

Rose diagrams of linear trends (Tappmeyer, 1974, Fig. 15, 16) show two strong linear sets, northeast and north-northeast. These directions appear on ERTS, aircraft and SLAR imagery and on fracture diagrams. Northwest trends are weaker on ERTS imagery than on any other representation - again the sun azimuth is probably a factor here. Northwest trending folds and monoclines in the Big Horn basin are difficult or impossible to discern on the spring imagery.

ERTS imagery clearly shows that the Big Trails fault and Badwater faults are connected as suggested by Tourtelot (1953). At the north end the Big Trails fault becomes an asymmetric anticline which intersects the Tensleep fault at the Dull Knife reservoir. This intersection is also the locale of some minor gold mineralization.

The Egbert monocline appears to be on line with several subtle linears to the south-southwest.

One strong northwest trend is that connecting the Red Spring and Wild Horse Butte anticlines with the Precambrian-Paleozoic contact to the southeast (1-1, Fig. 8).

On the fall, and especially the winter imagery, several small graben structures are apparent in stereoviewing. One of these had been mapped by Buffet (1958). They are not evident on the spring imagery.

The feature here named the Bates Creek linear can be traced from the Boysen Reservoir through Lysite Mountain to the southwest end of the Nowood fault. Segments of this linear include, previously mapped faults (Fanshawe, 1939; Wise, 1963; Tourtelot, 1946). SLAR imagery suggests some offset of ridges.

CONCLUSIONS

Without question, ERTS imagery provides a superb regional view of the geology of the Bighorn region. Structure is revealed mainly by drainage and linear analysis and to a lesser degree by tonal patterns. Many features can be related to known faults, monoclines and anticlines. Some faults and folds can be extended beyond previously mapped limits or connected with others formerly considered to be separate features. On the other hand some known structures, such as most of the marginal upthrusts, are not identifiable on the imagery. Field checking proved some linears to occur along fracture or shear zones, but many did not yield any clues on the ground. The tendency for plots of ERTS linears to correlate with those off aircraft photography and with ground fracture measurements indicates that the linears are mainly structure-controlled. N. to N.20°E., northeast and east-west trends predominate in ERTS imagery. The fewer northwest linears (in spite of the numerous northwest-trending folds) is due primarily to the southeast sun azimuth.

Mapping of lithologic units can be done only in a general way. Remote sensing units seldom correspond to mapped stratigraphic units.

Optimum geologic analysis requires all MSS bands from three seasons, winter (light but complete snow cover), spring and fall. From this analysis areas can be selected for detailed study utilizing aircraft photography and field checking.

The complexity of the structure of the range is well shown in the imagery. Many of the faults and other

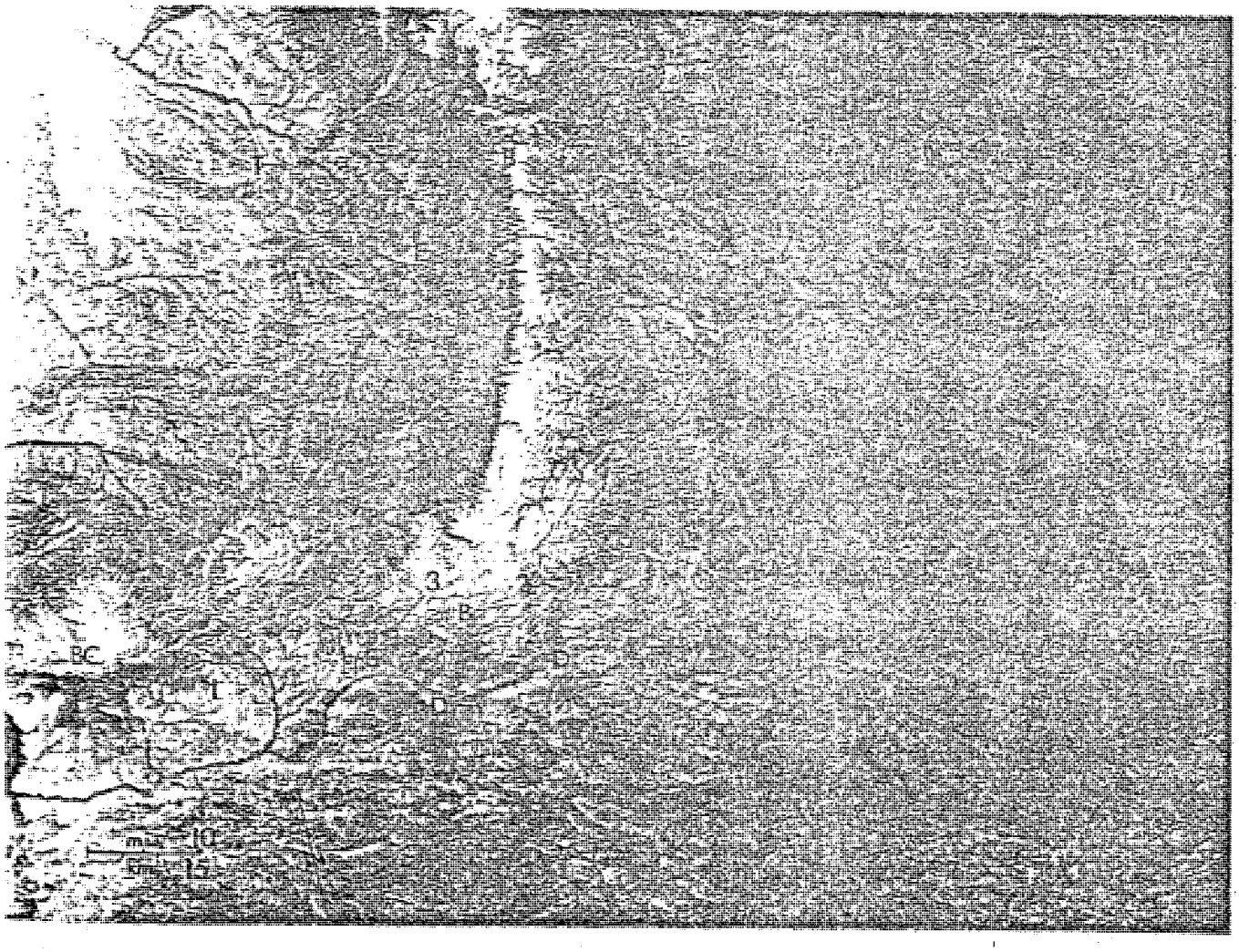


Figure 8.

T-T	Tensleep fault	TA	Tisdale anticline
E-E	Egbert monocline	TM	Table Mountain
B-B	Badwater- Big Trails fault	H	Horn area
N-N	Nowood fault	I-I	Red Spring - Wild Horse Butte trend
BC-BC	Bails Creek linear	2-2, 3-3	Probable faults
D-D	Dry Fork fault		

structural linears appear to be restricted to the uplift. The imagery reveals little surface evidence of these features in the basins. This suggests that much of the structure we see in the uplifts is due to erosion of old lines or zones of weakness. Though ground mapping has shown some reactivation along these lines in the Cenozoic, the amount of later movement has not been great and represents adjustments mainly within the uplift.

ACKNOWLEDGEMENTS

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GEOLOGIC MAPPING USING SPACE IMAGES

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ABSTRACT: Many parts of the world, and even large areas within the United States are inadequately mapped. Interpretation of standard black-and-white photographs has traditionally been an important tool for the geologist. New data made available through the ERTS-1 satellite and other earth resources sensing programs can provide still more data for the geologist by allowing him to take advantage of the spectral characteristics of the rocks as an aid in mapping. Image enhancement techniques, such as ratioing, show potential for better and more quantitative analysis of the sensor data.

An example, using ERTS-1 imagery as a base for regional mapping of the Arminto area of central Wyoming, illustrates the advantages and limitations of the ERTS-1 data. Portions of the Arminto area were also mapped using Skylab and high-altitude aerial photography. Comparison of these maps with the Geologic Map of Wyoming (Love and others 1955) and the available detailed maps in the area reveals definite resolution limitations of the satellite data.

Color and synoptic coverage of broad areas are other important attributes of the ERTS satellite data. Skylab color photography has these advantages and the additional advantages of higher resolution and stereoscopic coverage. Aerial photography provides the additional detail necessary for accurate interpretation in geologically complex areas. Together, the ERTS, Skylab, and aircraft imagery provide an essential tool for geologic mapping that far exceeds the capability of standard aerial photography.

INTRODUCTION

State-of-the-art space imagery is not an optimum product for geologic mapping. Obviously the geologist needs the highest resolution image possible for accurate work, and in many areas most- or all of the mapping must be done by ground methods. Even in areas where vegetation is sparse and aircraft imagery excellent, ground surveys must supplement photogeologic mapping. Until recently, many geologists have abandoned photogeologic methods on the assumption that photogeologic methods are not quantitative enough for accurate mapping; or, if useful at all, the main use will be outside the United States because we are assumed to have essentially mapped the country. Studies by the United States Geological Survey (Kinney, 1970, p. 18) show that only about 25% of the country (post-1930 mapping) has been mapped at scales as large as 1:62,500. However, if we go to a scale of 1:250,000 or 1:500,000, a scale where space images might be most useful, we might assume that most of the United States is adequately mapped. Figure 1 shows the status of modern published and available unpublished mapping in the area covered by the Arminto AMS sheet of central Wyoming. This index has recently been brought up to date by J. D. Love for use in compiling the new state geologic map. Clearly we have some major gaps in the mapping and we have similar gaps elsewhere in the state, but the Arminto area is one of the worst so we selected it to see if spacecraft imagery could be helpful in geologic mapping.

LIMITATIONS OF TODAY'S METHODOLOGY

Photogeologic mapping using standard black and white products is basically an attempt to map contacts of photo units as expressed by tonal contrasts, texture, and geomorphic features, and to map faults and other structures by use of stereoscopic interpretation. Tonal contrasts expressed on black-and-white prints are useful in mapping lithology, but they can seldom be used to identify rock types. Laboratory determined reflectance spectra for common rocks show differences in the visible and near-infrared regions due primarily to electronic processes in the cation or impurity ions (iron the most common source) and to vibrational processes in hydroxyl groups or molecular water, and in the far infrared (9-12 um) due primarily to silica content (Hunt and Salisbury, 1971). The reflectance spectra also show variation in overall reflectances for rocks depending, in part, on electronic processes which can produce an extremely sharp cutoff in the visible or near-infrared spectrum, or continuous absorption throughout the entire range (Hunt, Salisbury, and Lenoff, 1971, p. 1-3). Thus rock spectra show two main characteristics: narrow absorption bands due mainly to the presence of iron, hydroxyl groups, water and silica, and broad reflectance differences or brightness differences. A granite, for example, has a relatively high spectral reflectance as compared with basalt, basalt may show absorption bands due to iron content not shown by granite, and silica absorption bands in granite are recorded at different wavelengths than those in basalt (Figure 2). These spectral differences appear to offer a possibility for remote identification of rocks and a number of studies have been undertaken, primarily using aircraft systems, to

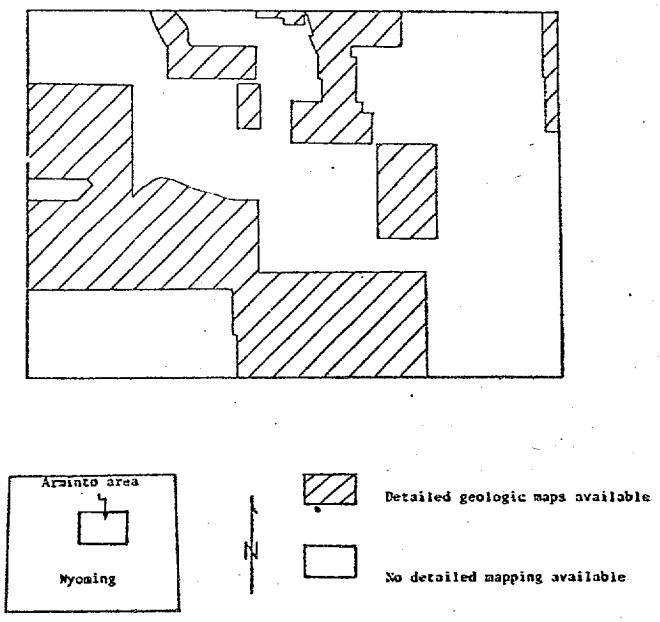


Figure 1. Index showing areas of available detailed coverage within the Arminto area.

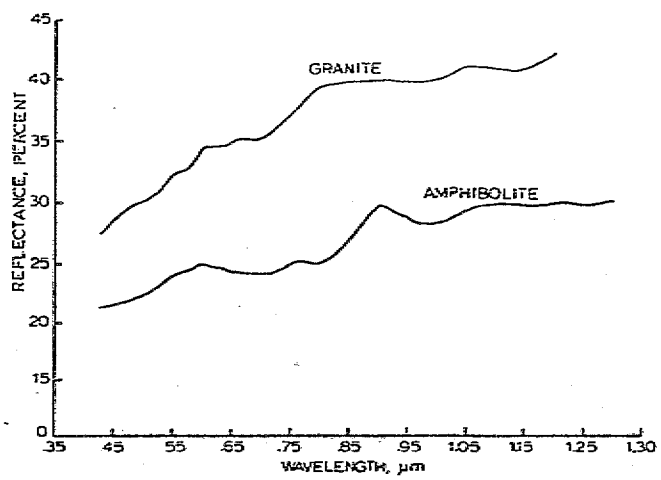
determine if rocks can indeed be identified by use of spectral difference. One of the most comprehensive studies was that of Lyons (Lyons and Patterson, 1969, p. 527-552) at Stanford who has had some success in identifying rocks by taking advantage of the shift in silica absorption band with silica content in the far infrared. This study made use of an aircraft mounted spectrometer and radiometer. Characteristic spectra of common rocks were compared with those of the target or unknown as determined by the spectrometer, and under optimum conditions rock types and contacts could be mapped along the straight-line path of the spectrometer. The method is subject to a number of limitations that will be discussed, but for geologic mapping a major limitation is that information is confined to the single narrow path of the spectrometer and is difficult to extrapolate into other areas for mapping. An approach that uses the same silica shift principle in mapping rocks but makes use of a multispectral scanner instead of a spectrometer has been proposed and tested by Vincent (Vincent and Thompson, 1971, p. 247-252). Instead of using the complete rock spectra as was done by Lyons, selected bands of the spectra (i.e. 8.2-10.9 um/9.4-12.1 um) are ratioed and ratio images are produced that are useful in distinguishing silica-rich and silica-poor rocks. This method is less specific than that of Lyons, but multispectral scanners produce image data so that maps can be generated from the interpretations and identifications.

The ratio approach has been extended to make use of iron-absorption bands by a number of investigators (Vincent, 1972, p. 1239-1247; Rowan, 1972, p. 60-1-60-18), and because the MSS scanner of ERTS includes near infrared bands the technique has been used to map iron-rich rocks and alteration zones by use of ERTS data (Vincent, 1973; Rowan and others, 1973).

These various techniques plus others using related approaches (Watson, 1972; Pohn, Offield, and Watson, 1972; Watson, Rowan, and Offield, 1971) offer promise for eventual quantitization of geologic mapping, but, as is true for many geologic problems, the number of variables that must be considered to apply these techniques to actual field problems is very large. Factors that affect rock spectra include grain size, grain orientation, degree of weathering, vegetation cover, sun angle and azimuth, viewing geometry, slope angle, temperature, water saturation, atmospheric conditions and depth of the atmospheric column, shadowing, and such common factors as strike and dip of outcropping beds. No technique has been developed to take all of these factors into account although some are considered in most experiments. Statistical methods that essentially map significant reflectance differences in a given area or use training sets to map a certain tone or density that may characterize a rock in a given area (Anuta and others, 1971; Smedes and others, 1972; Watson and Rowan, 1971) are useful but, again, cannot be applied to general mapping because of variables cited above. The 1974 state-of-the-art suggests that enhancement techniques may be useful for mineral exploration under controlled conditions (i.e. where the method is tailored to a specific area) but general geologic mapping is still best done by the experienced photogeologist using standard photogeologic techniques.

NASA SYSTEM

The NASA system offers the photogeologist a number of products that were not previously available. Most systems include multiband images representing selected parts of the spectrum plus color and color infrared images. The multiband images generally include green, red and near infrared bands that can be used by geologists for topical mapping. For example, near infrared images show bodies of water and water-saturated soils distinctly (dark colored to black) because the near infrared energy is strongly absorbed by water. In addition, the near infrared may show the best contrast between iron-rich and iron-poor rocks (basalt and granite) because of the presence of the iron absorption bands in this wave length. Red bands show vegetated areas as very dark objects because of chlorophyll absorption of light in this wavelength. Thus rocks marked by characteristic vegetation may be mapped much better by use of the red band image. Green band images are not especially useful for



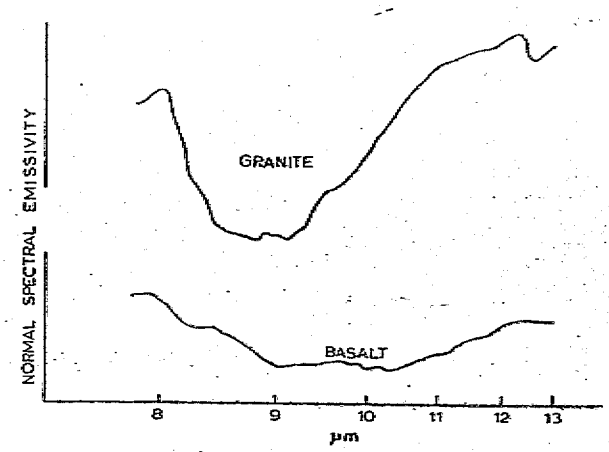


Figure 2. Comparisons of reflectance and emissivity spectra for acidic and mafic rocks. The reflectance curve for the mafic rock shows a reflectance low (absorption) at about 0.7 m and 1.0 m. The thermal emissivity curves show a decided shift in the emissivity low toward shorter wavelength due to the increased silica content of the granitic rock.

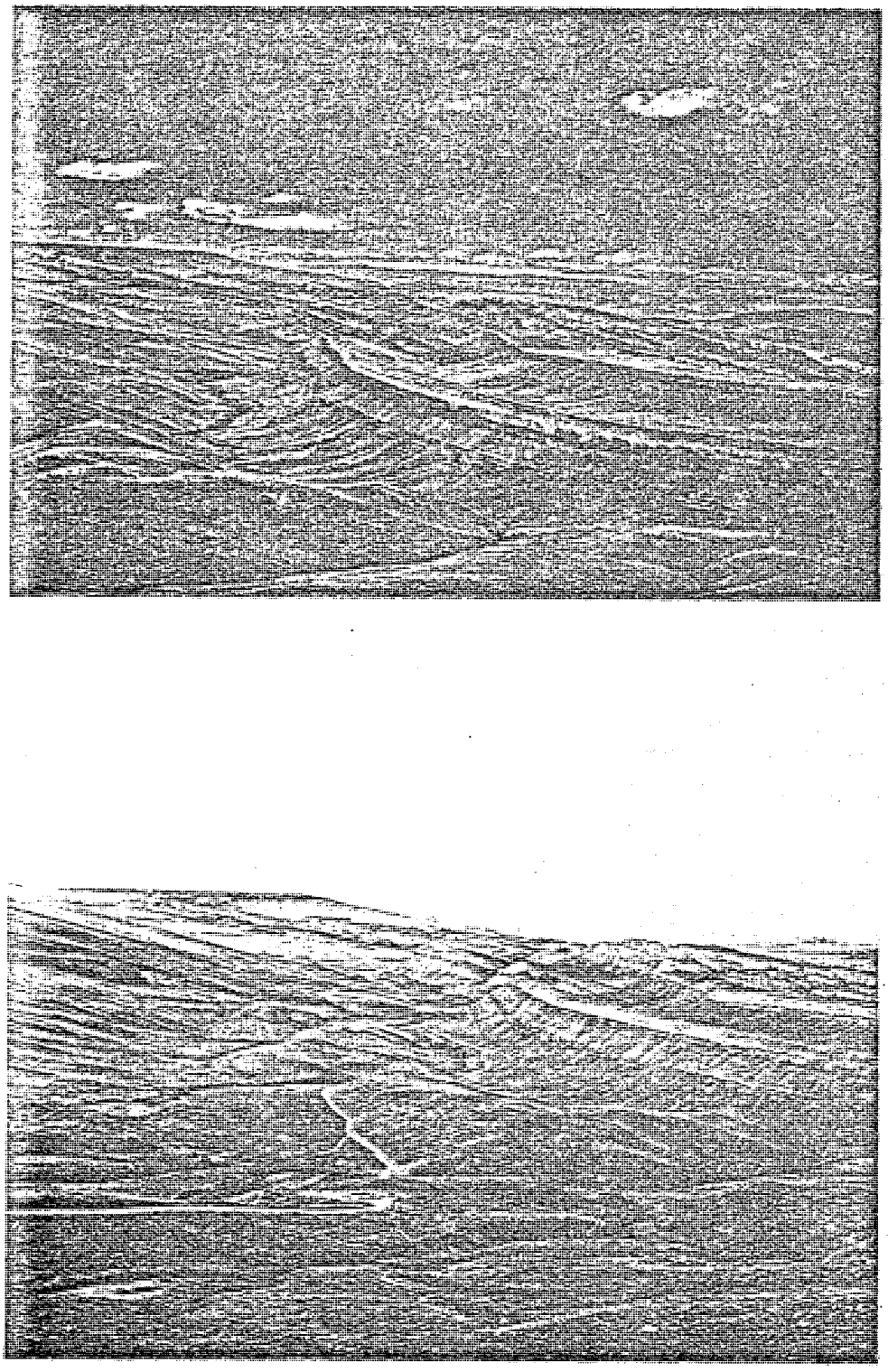


Figure 3. Comparison of color photograph (top) and color infrared photograph (bottom) of the Cedar Ridge red beds on the east flank of the Wind River Mountains.

geologic mapping, but they are of great value to the sedimentologists who may be interested in mapping suspended sediment in water bodies because water does not strongly absorb this wave length and the sedimentologist can "see through" the water and pick up the reflectance of suspended particles.

Color and color infrared images may be generated by combining bands or may be available as photographic images. These products are better suited for geologic mapping because they add the additional dimension of color for mapping lithologies. No geologist will claim that color is diagnostic of rock type, but in a given region a particular rock unit often displays a characteristic color over a large outcrop area. Standard color-transparencies (preferred for mapping because of higher resolution) and prints are adopted by most geologists because they show rocks in a mode the geologist is accustomed to, but color infrared is just as useful and perhaps a better mapping tool because a good color infrared image is sharper due to better haze penetration, and, if rocks being mapped have a strong contrast in iron content, there is a greater tonal contrast in the infrared. Inasmuch as the color infrared image combines the red, which shows low reflectance for vegetation, with the infrared, which shows high reflectance for vegetation, vegetation is notably enhanced, and rock units with vegetation expression are readily mapped. In any event once the geologist is familiar with the color shift as shown in Figure 3, he can map as well or better with infrared.

APPLICATION

The best approach we have found for geologic mapping using space images is to try to recognize units with distinctive tone (+ texture) that can be used as marker beds in a given region, and to use these beds along with other standard recognition parameters for mapping decisions. Figure 4 shows laboratory reflectance spectra

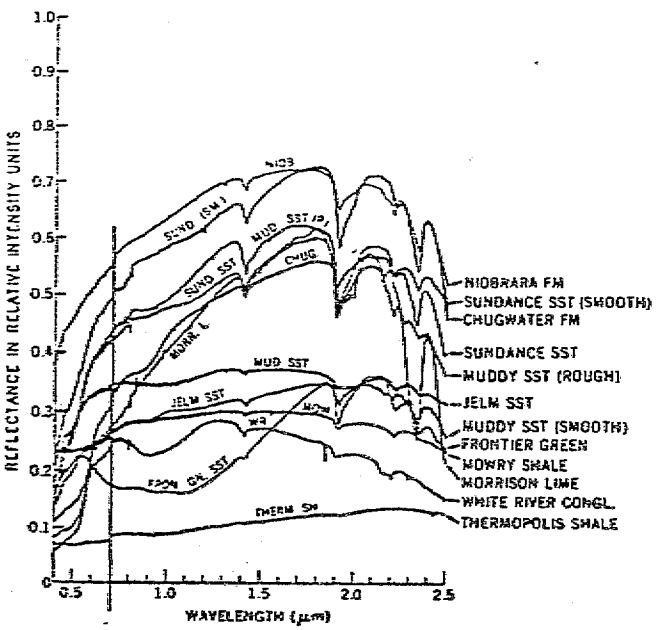


Figure 4. Spectral response curves for a group of rocks from Wyoming determined on a Carey 90 reflectance spectrometer (from Short and Lowman, 1973, Fig. 30, p. 91).

determined at Goddard Space Flight Center (Short and Lowman, 1973, p. 9) for a typical suite of Wyoming sedimentary rocks. The spectra are not sufficiently distinctive to be diagnostic of rock type, and, as noted by Short and Lowman (1973, p. 18), several individual rocks displayed greater variation between spectra from fresh and weathered surfaces an inch apart than between quite different rock types. Yet it is apparent that one sedimentary rock group, the Cretaceous shales, has exceedingly low reflectance as compared with other units. These beds of the upper Thermopolis Shale and lower Mowry Shale contrast strongly with other units as the laboratory spectra predict and can be recognized through most of their outcrop area (Fig. 5). Furthermore, since we have the advantage of color images, color can also be used for mapping, and, throughout most of Wyoming, Permo-Triassic red beds make excellent marker units.

A geologic map (Fig. 6) of the Arminto area of central Wyoming was prepared from interpretation of an ERTS infrared color composite (Fig. 5) using a Bausch and Lomb zoom transfer microscope. When compared with the state geologic map, (Fig. 7) it is apparent that units mapped from tonal variations are surprisingly close to those chosen as formations by field geologists — particularly since most of these major units are rock-vegetation units.

Figure 8 compares the southeastern quarter of the Arminto AMS map with same area on the 1955 geologic map of Wyoming. Much of this area has not been mapped in detail and no mapping is available in published or open-file form. The geologic map shows nine lithologic subdivisions whereas the ERTS photogeologic map shows twenty-five lithologic (?) subdivisions. This area has not been fully field-checked so we cannot be certain that all subdivisions shown on the ERTS photogeologic map correspond to changes in lithology. The large area shown as Cody Shale (Kc) on the geologic map has been subdivided into several units; the areas known as Kn (CS) and Kn (S) probably correspond to calcareous shales and shales of the Niobrara Formation. The area shown as Kc is typical Cody Shale. The area shown as Kstc is the Shannon Sandstone member of the Cody Shale. The area shown as Kc(b) is Cody Shale with very little vegetative cover and that shown as Kc(v) is Cody Shale with irregular vegetative cover. Finally, the lens shown as Kss may be the Sussex Sandstone member of the Cody Shale. The reason for the irregular vegetative cover on the upper Cody Shale bed has not been determined but it Kc(b) does coincide with the location of a major oil field. The odd-shaped area in T.38 N., Rs. 81 and 82 W. is an area where the natural vegetation has been disrupted by extensive spraying to kill sagebrush so its significance is probably not lithologic.

The Mesaverde Formation can also be subdivided into the Parkman Sandstone Member (Kmvp), a shale unit (Kmvs), and an upper unit that is probably the Teapot Sandstone member (Kmvtp). Distinctions were also made within the Fox Hills Sandstone (Kfh) and Lance Formation (Kl), but their significance is not known. A unit designated (Tfus) may be a lower, massive sandstone of the Fort Union Formation and a unit designated (Tuss) may be a sandstone of the Wasatch Formation. Finally, stabilized sand dunes (Qsc), active sand dunes (Qsa), and alluvium (Qal) are readily mapped.

The southeastern quarter of the Arminto AMS sheet is particularly well suited for regional geologic mapping with ERTS color infrared because the various formations display good vegetation control, have low dips, and exhibit a fairly broad outcrop area. Other areas are not so suitable for mapping because dips are steeper, structure more complicated, and vegetation tends to mask rock types rather than enhance them. A typical area of this type is outlined on the ERTS Arminto map in the north-central or Horn area (Fig. 6). Comparison of the ERTS Horn area map (Fig. 6) with the same area on the state geologic map (Fig. 7) shows the ERTS map to be inaccurate due to the above stated limitations combined with the 100-meter resolution of ERTS.

The Skylab photographs taken with S-190A multispectral camera facility and the S-190B earth terrain camera offer a solution to ERTS resolution problems. Figure 9 is an example of a Skylab high resolution panchromatic photograph taken with the S-190B earth terrain camera of the Horn area. This photograph has a resolution approaching 10 meters compared with an ERTS resolution of about 100 meters. This Skylab photograph also has the advantage of stereo-coverage so structural studies are superior to those possible with ERTS where side lap is limited to 40 percent.

Geologic mapping with Skylab photographs can be done by enlarging the high-resolution S-190B photograph to 1:125,000 and mapping on mylar overlay. Structural and lithologic information can be added by using stereo-pairs of S-190A film positives, especially the color and color infrared photographs. If adequate control, such as roads, towns, and streams, is available, a base grid of Township and Range can be added to the geologic map by projection. There is generally so little distortion in the space photograph that a grid can be fitted with little or no adjustment.

The Skylab map of the Horn area (Fig. 10) can be compared with the same area on the 1955 state geologic map (Fig. 7). This map is not an improvement over the state geologic map partly because of too heavy vegetation in the northwest quarter and cloud cover in the northeast. It is a satisfactory reconnaissance map at 1:250,000, and in some areas, (southeast) it is actually more detailed than the state geologic map. It is unquestionably a marked improvement over the ERTS map of this area (Fig. 6).

Skylab photographs can also be utilized to select areas that require more detailed investigation (such as the area outlined in Figure 10). This area has been selected for photogeologic mapping using aircraft imagery. A geologic map was prepared by use of a B&L zoom transfer scope augmented by use of stereopairs of film positives on a Richards stereo-photointerpretation table. The photogeologic map (Fig. 11a) is quite comparable to field geologic maps prepared at a scale of 1:24,000 except in areas of heavy vegetative cover. A major difference between the geologic and photogeologic map is the choice of map units. Photogeologic units were selected by choosing units that show distinctive and consistent tone on color infrared film positives. In this area shales are the best marker units — 8 out of 11 units chosen on the basis of consistent tone were shales. As can be seen on Figure 12, photogeologic units may or may not correspond to units mapped as formations by field geologists. For exmaple, the Skull Creek Shale (Ksc, Fig. 12) (Thermopolis Formation equivalent) of this area as defined by the field geologist (Hose, 1955) is a three-fold unit consisting of a lower subdivision of alternating gray siltstone and grayish-black shale, a middle, ridge-forming, siltstone bed and an upper unit of grayish-black, soft, flakey shale. The upper unit (Kscus, Fig. 12) exhibits a distinctive dark blue tone on the color infrared photograph and was chosen as a marker unit. The Cloverly Formation (Kcv, Fig. 12) consists of a basal sandstone, overlain by grayish-black shale capped by a resistant brownish-gray siltstone the photogeologic unit (Kcrus, Fig. 12) that is most distinctive on color infrared is the grayish-black shale that has a dark brown tone on the photograph. Other photogeologic units include an upper, olive-gray, silty, calcareous shale (Jsus, Fig. 12) of the Sundance Formation that is distinctive and uniform on the infrared photograph, a lower, middle part of the Mowry Formation (Kmrusi, Fig. 12) that is highly reflective and appears bright blue on the photograph. Other units are mapped on the infrared photograph much as they are by field geologists — for example Permo-Triassic red beds and red beds of the Amsden Formation.

The departure in selection of map units has the obvious disadvantage that the photogeologic mapping cannot be readily correlated with field maps. However, the aircraft photography is usually detailed enough so that units (or combinations of rock units) mapped as formations by field geologists can be selected and mapped using the photograph. This problem may require some rethinking of map units by geologists to see if the photo units are superior to formations as previously defined or visa versa. Perhaps the best choice lies in a compromise — we may wish to use standard formations in most cases, but in some instances subdivisions may be made by photointerpretation even though they are simply not apparent on the ground.

Comparison of the geologic and aircraft map (Fig. 11) of the Horn area shows several major differences between the two. The geologic map is less accurate in Sec. 32, T.46 N., R. 83 W., and in Secs. 4 and 5, T. 45 N., R. 83 W. where vegetation cover makes it impossible to map structural detail as accurately as in the field. On the other hand, the photogeologic map may be more accurate in the southeast (T.45 N., R. 82 W.) where shales of the Frontier Formation and Cody Shale have been subdivided into four units based on tonal differences that can be seen on the photograph rather than the two units used by field geologists. If field checks show that these four subdivisions are indeed lithologic units, the structure in the hinge area of the Horn Fault is more complicated than suggested by earlier mapping.

In summary, the NASA, ERTS, Skylab, and aircraft products — especially the color infrared and color film positives are the best tools publically available for photogeologic mapping today. They are not competitive with, nor are they a substitute for, careful field studies, but we believe that even in situations where money and time are available for detailed field studies, the geologist should utilize these images — failure to do so might be analogous to studying a thin section with a 100X objective only.

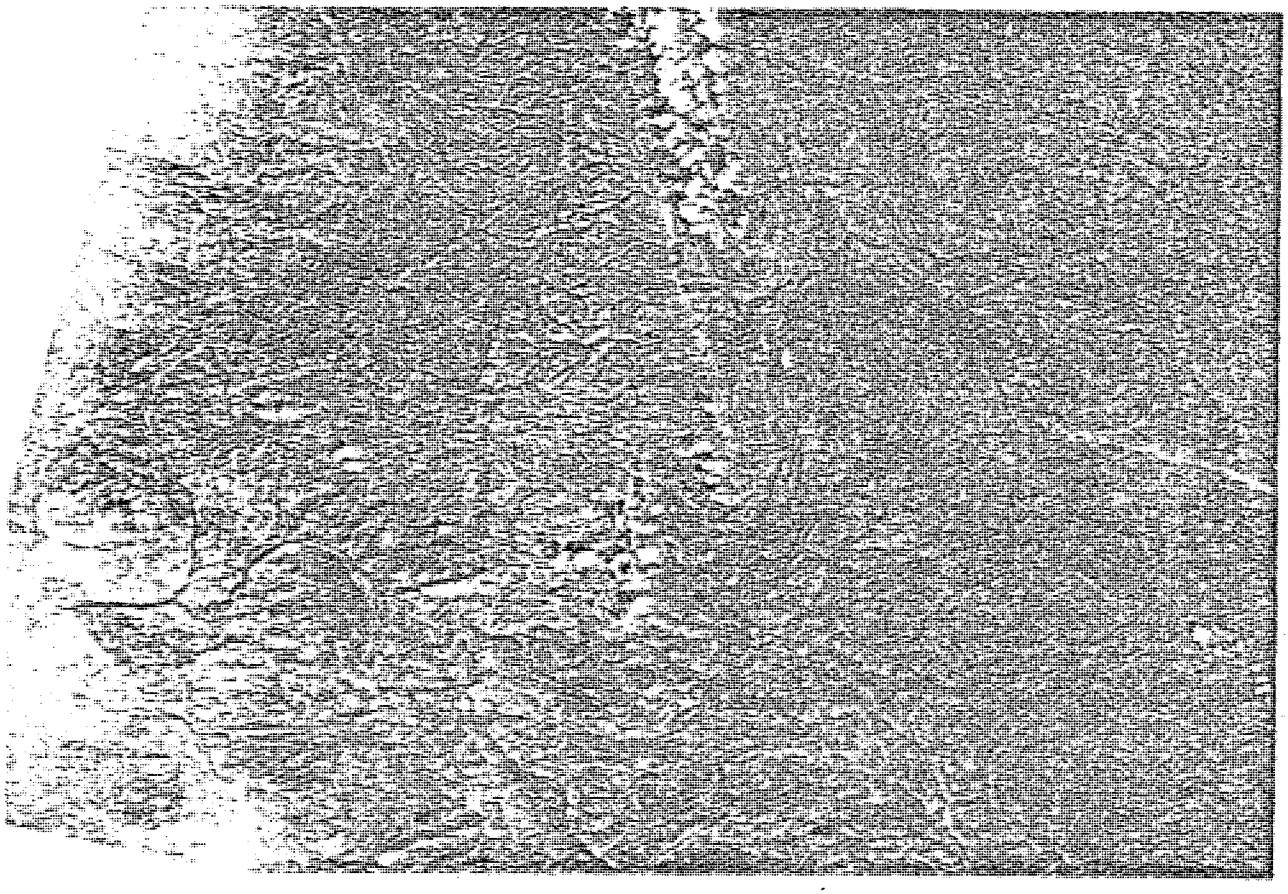


Figure 5. Color infrared ERTS image of the area covered by the Arminto AMS sheet of central Wyoming. ERTS-1 color composite 1030-17235. The dark blue units in the center of this image are Cretaceous shales with distinctive low reflectance. These are useful as marker beds in geologic mapping.

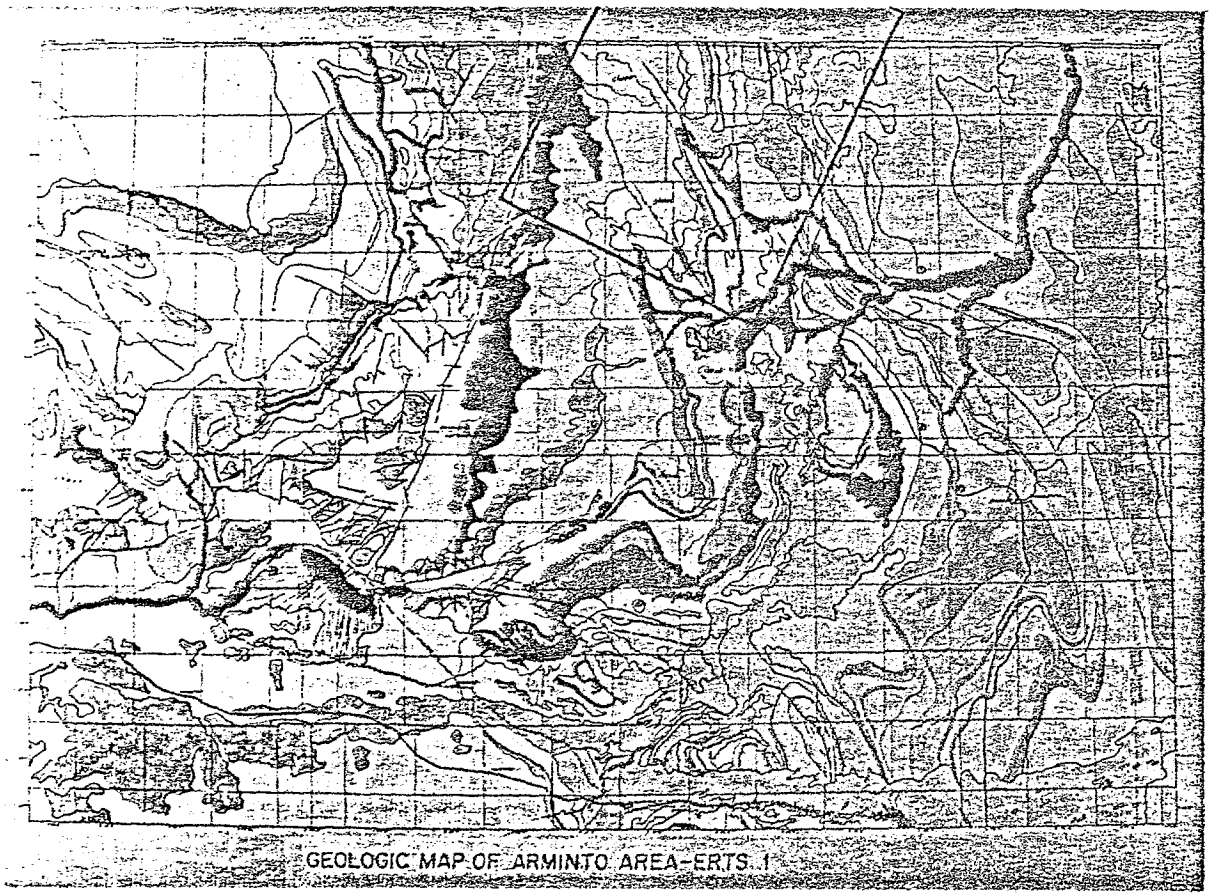


Figure 6. Reconnaissance geologic map of the Arminto area of central Wyoming prepared by use of an ERTS infra-red color composite (Fig. 5). Radial line pattern in Tps 38 and 39 N., and Rs. 88, 89, 92, and 93 W. are probably a result of boulder and cobble trains on pediment surfaces. The coarse clastics are probably derived from Paleocene conglomerates. Map is color coded to approximate color of rock-vegetation units as seen on ERTS image — bright red is Quaternary alluvium with active vegetation growth, blue is shale, dark blue is black shale, yellow is red beds, and flesh-colored units are sandstone or limestones of high reflectance and sparse vegetation. Area outlined in black is also mapped using Skylab 190B photographs (Fig. 10). Compare reconnaissance geologic map with state geologic map of same area (Fig. 7).

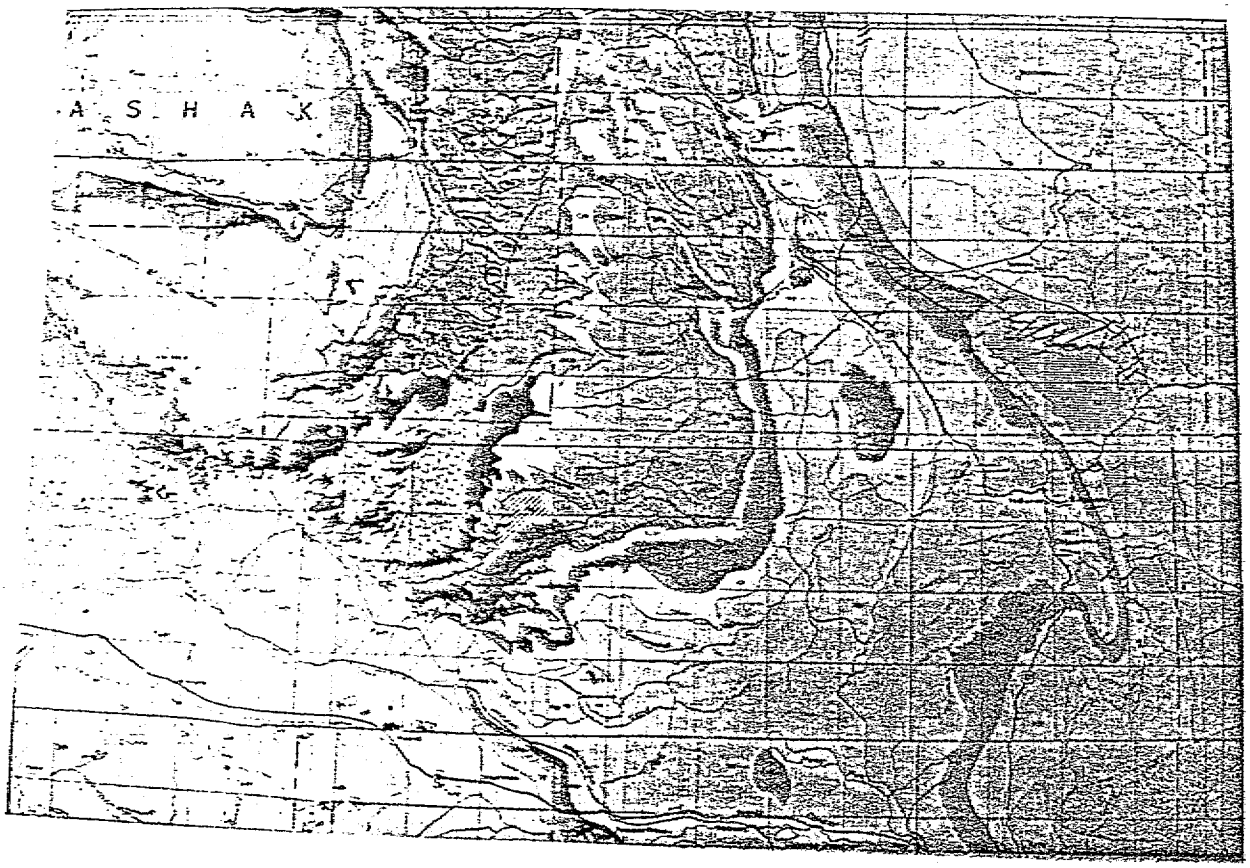
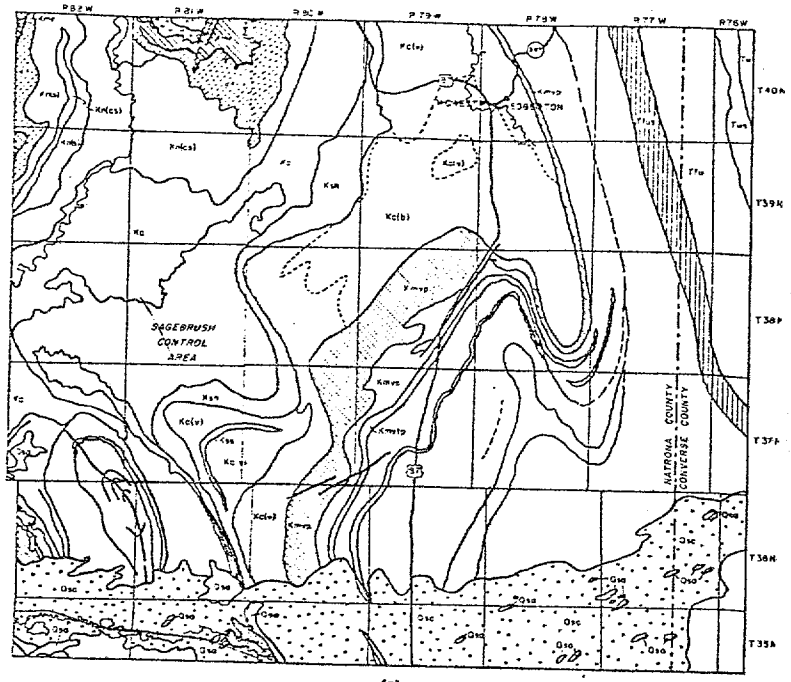
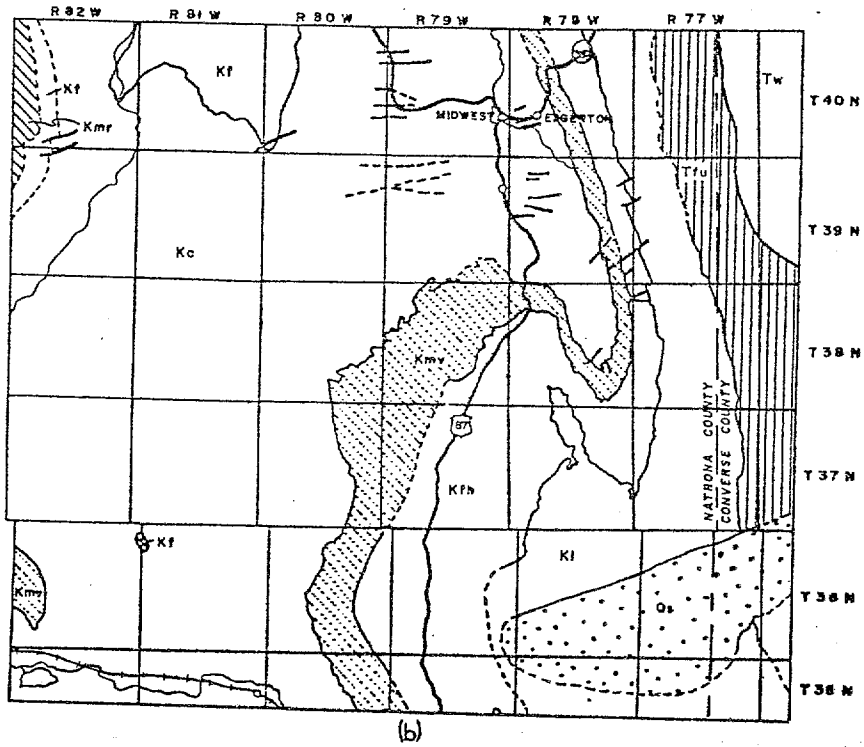


Figure 7. Geologic map of the Arminto area of central Wyoming after Love and others (1955). Compare with Figure 6.



(a)



(b)

Figure 8. Details of the southeast ¼ of the ERTS Arminto map (Fig. 6) compared with the same area on the state geologic map of Wyoming (b). See text for explanation of units. Geologic map of Wyoming after Love and others (1955).

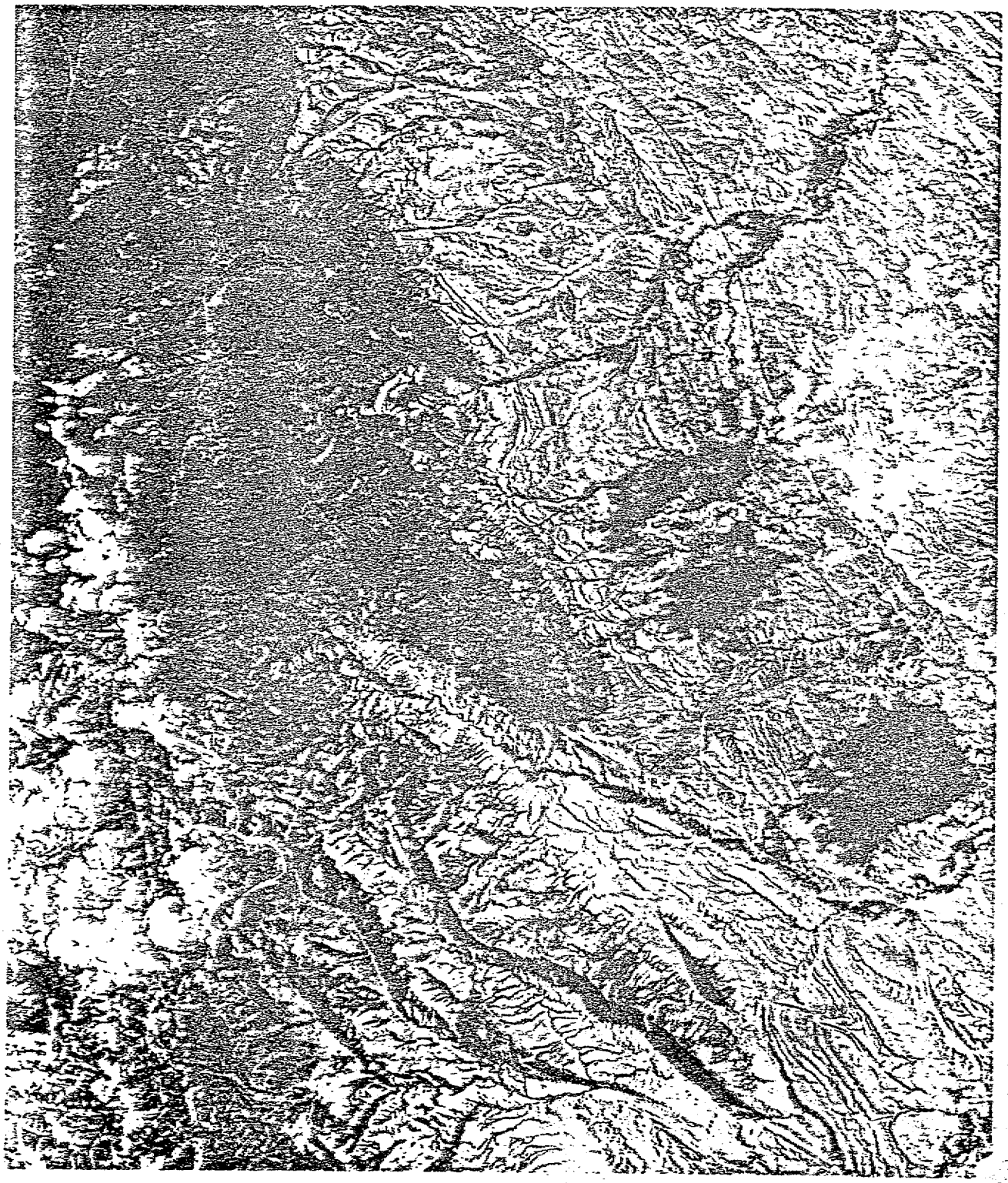


Figure 9. Skylab 190B photograph of the Horn area shown outlined in black on Figure 6 (Skylab mission 2, pass 10, June 13, 1973).

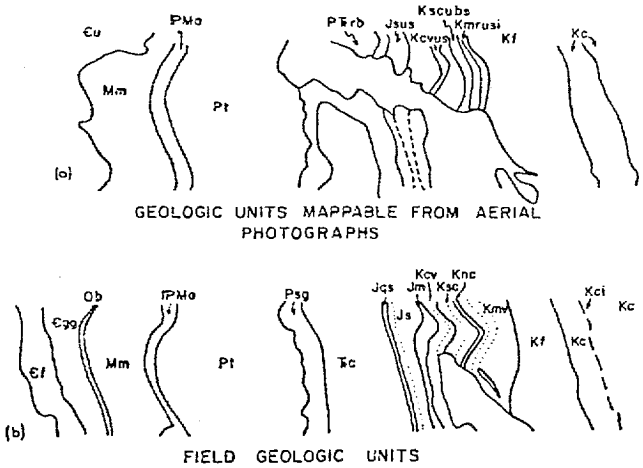


Figure 12. Comparison of photogeologic map units and units chosen by field geologists in part of the Horn area. See text for explanation of units.

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INTEGRATION OF GEOLOGICAL REMOTE-SENSING TECHNIQUES IN SUBSURFACE ANALYSIS

U.S. GEOLOGICAL SURVEY

OPEN-FILE REPORT 76-402

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

INTEGRATION OF GEOLOGICAL REMOTE-SENSING TECHNIQUES IN SUBSURFACE ANALYSIS

By James V. Taranik and Charles M. Trautwein

Open-File Report 76-402

Sioux Falls, South Dakota

May 1976

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INTEGRATION OF GEOLOGICAL REMOTE-SENSING 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).

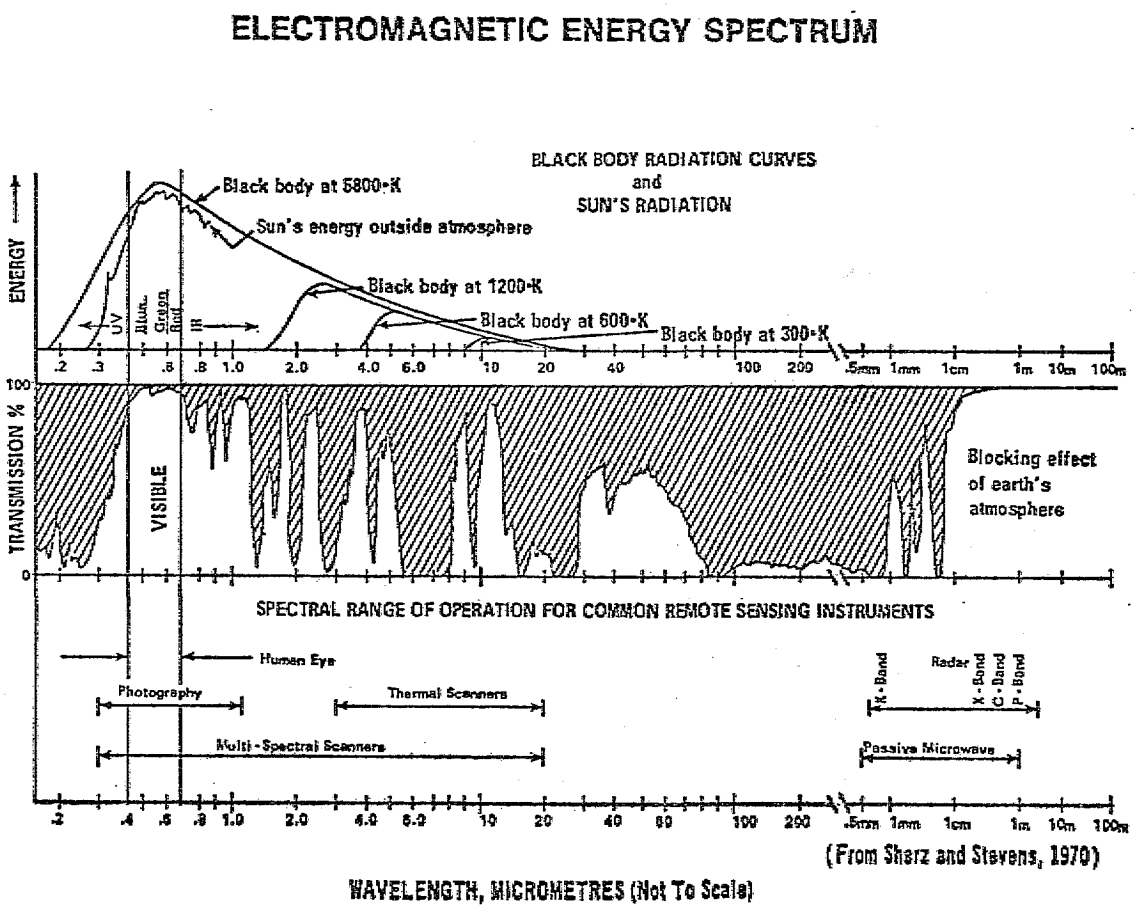


Figure 1: Electromagnetic energy spectrum.

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

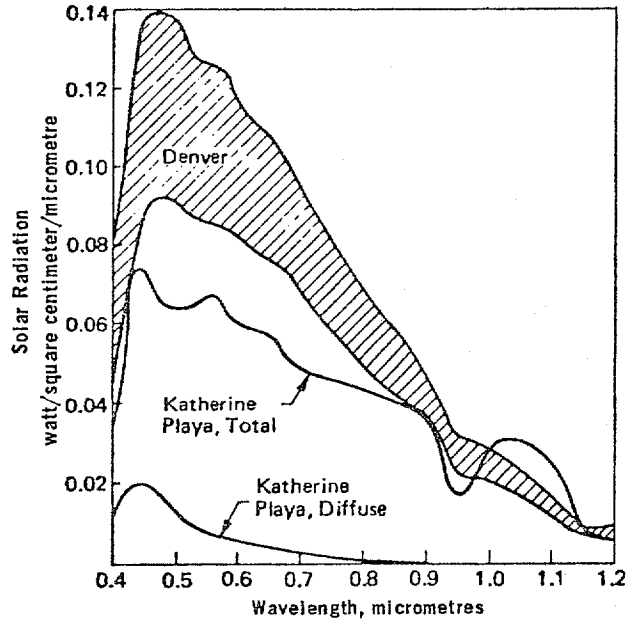


Figure 2: Variations in solar incident radiation between 0940 and 1430 hours in the spring near Denver, Colorado (shaded). Upper curve is for 1430 hours. The curve for Katherine Playa, New Mexico shows total solar radiation (daylight) for a typical clear winter day in a dry atmosphere. The skylight curve 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

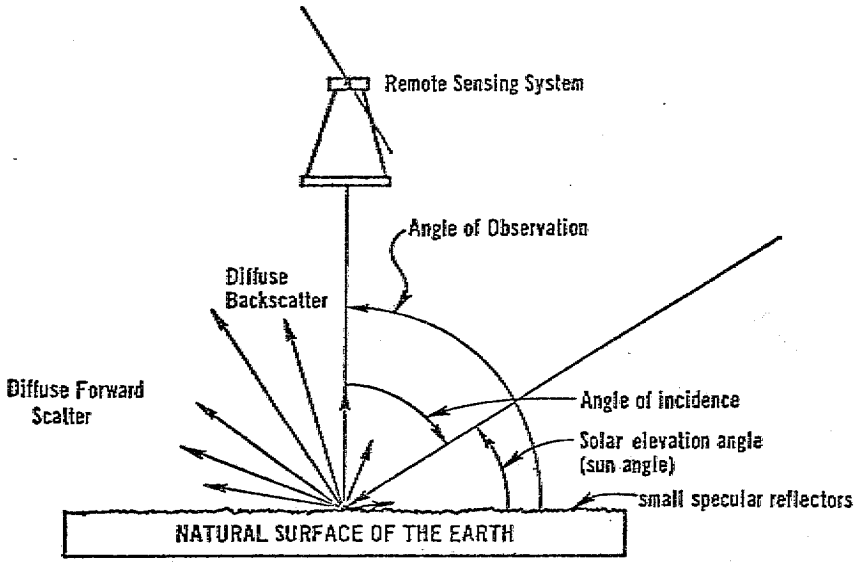


Figure 3: Reflection of incident solar radiation from natural surfaces

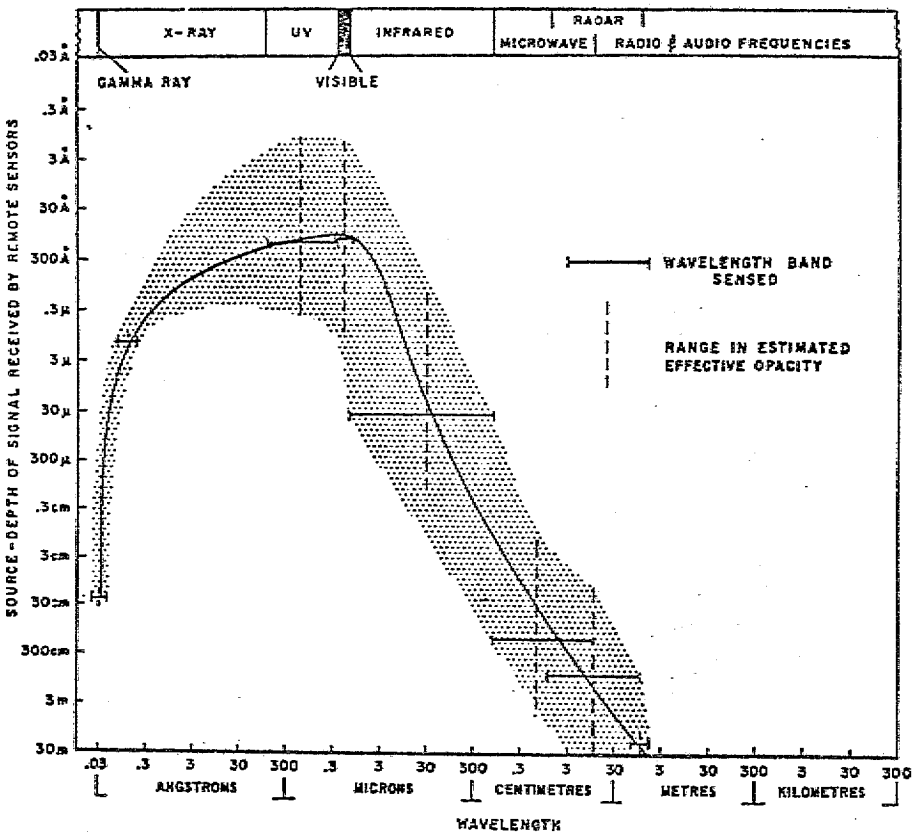


Fig. 4 Generalized absorption-coefficient curve for dry natural materials derived from terrestrial data; indicates estimated source-depth of information in received signal expected from lunar surface materials. In part after Bodgley and Lyon, 1964, N.Y. Acad. Sci., and Second Symposium on Remote Sensing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

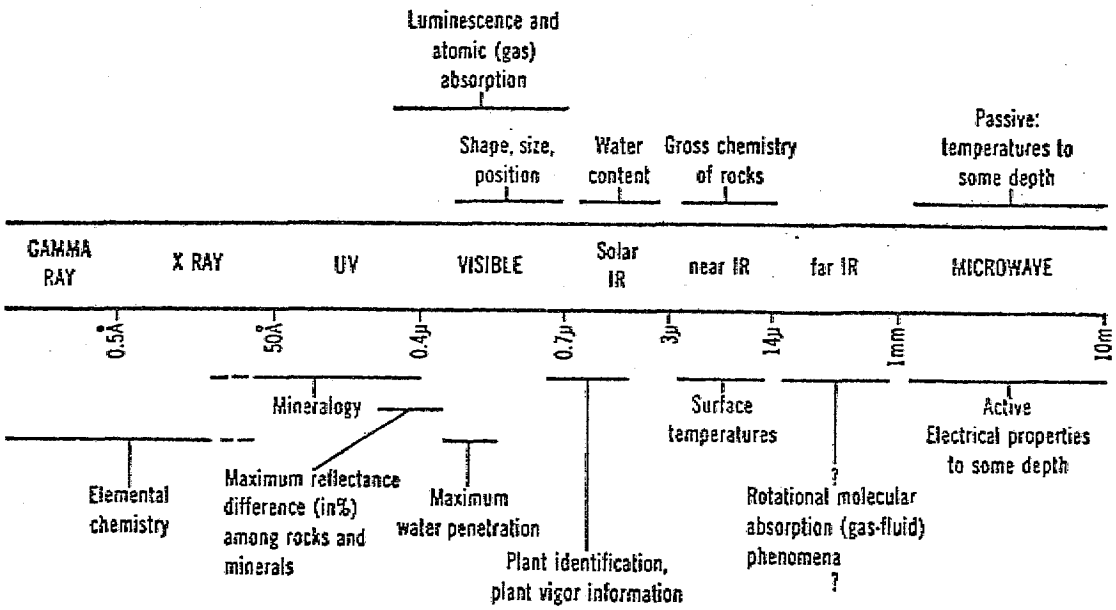
KINDS OF WAVES	WAVELENGTH (cm)	FREQUENCY (Hz)	USUAL SOURCE	USUAL METHOD OF DETECTION
Ultraviolet	$3\text{-}4\times10^{-5}$	$f=\frac{c}{\lambda}$	Disturbance of intermediate electrons	Fluorescence chemical effect
Visible		$c=3\times10^{10}$ cm/sec.	Disturbance of valence electrons	Eye, photo-chemical effect, photo-detectors
Blue	$4\text{-}5\times10^{-5}$			
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)	$0.7\text{-}1.5\times10^{-4}$			
Thermal				
(1)	3.5-5.5 "			
(2)	8.0-14 "			
Microwave			Molecular motion. Electrical resonance of tuned circuits, antennas	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

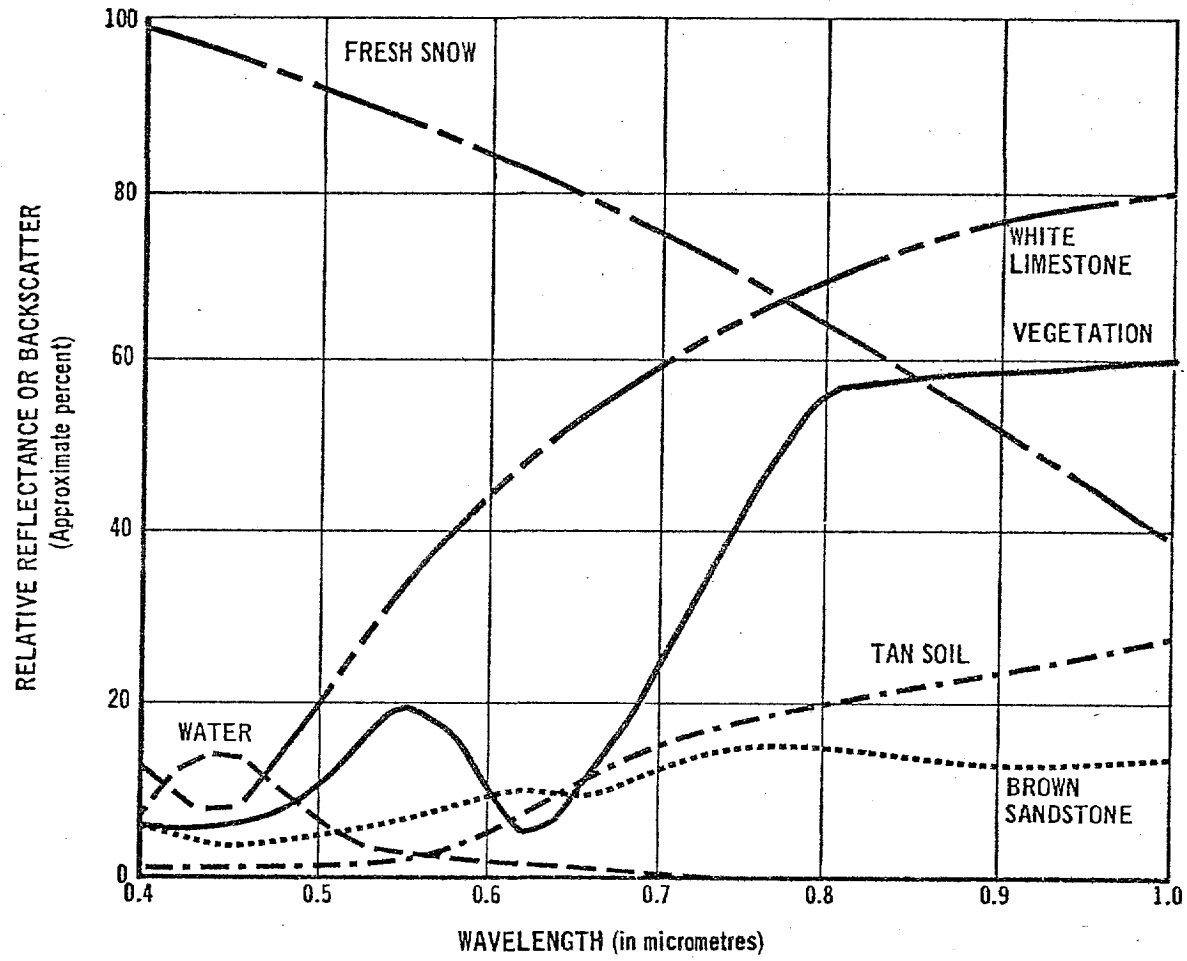


FIGURE 6: General spectral characteristics of main cover types
Some data from G. Moore, personal communication

IDEALIZED CURVES SHOWING RELATIVE REFLECTANCE OR BACKSCATTER FROM COVER TYPES

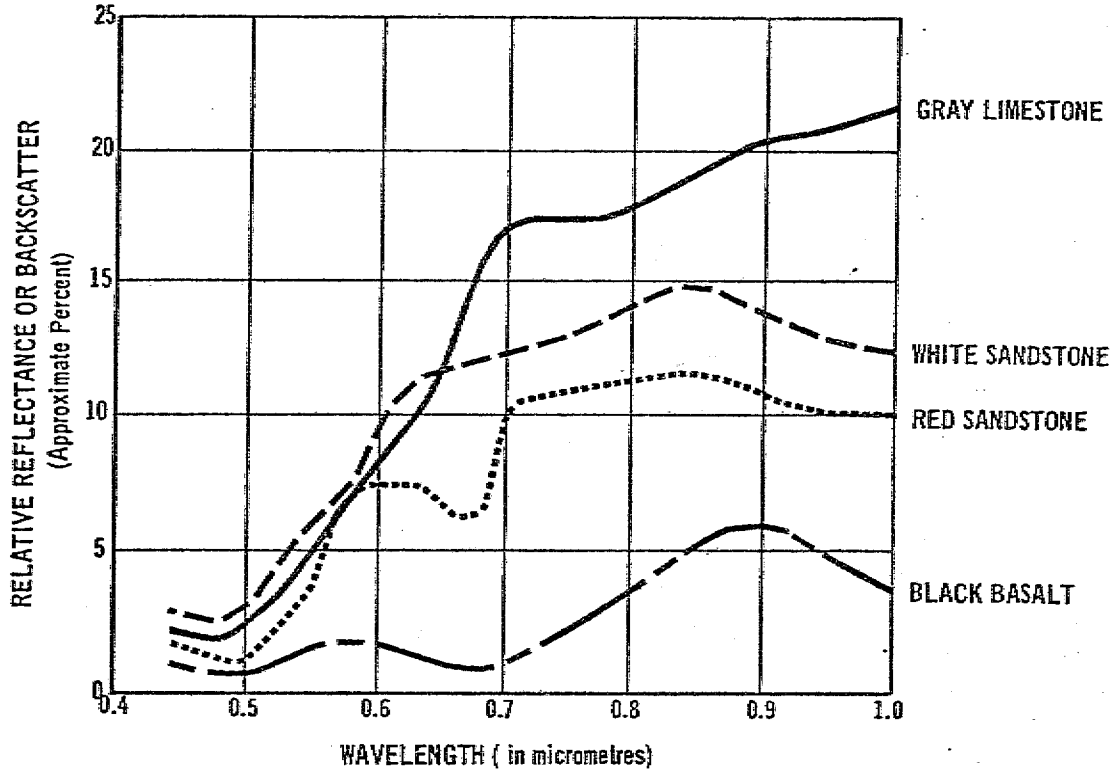


FIGURE 7: Spectral characteristics of rock types. Data in unpublished form furnished by Orr and from visual analysis

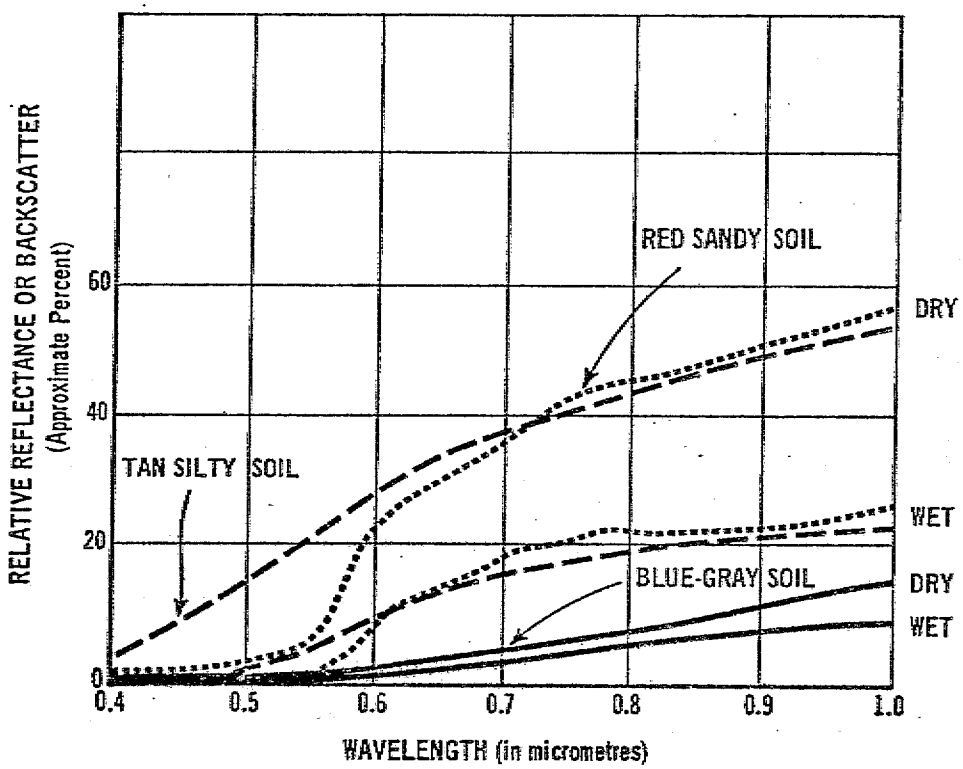


FIGURE 8: Spectral characteristics of Soils, data from H.R. Condit, 1970

IDEALIZED CURVES SHOWING RELATIVE REFLECTANCE OR BACKSCATTER FROM COVER TYPES

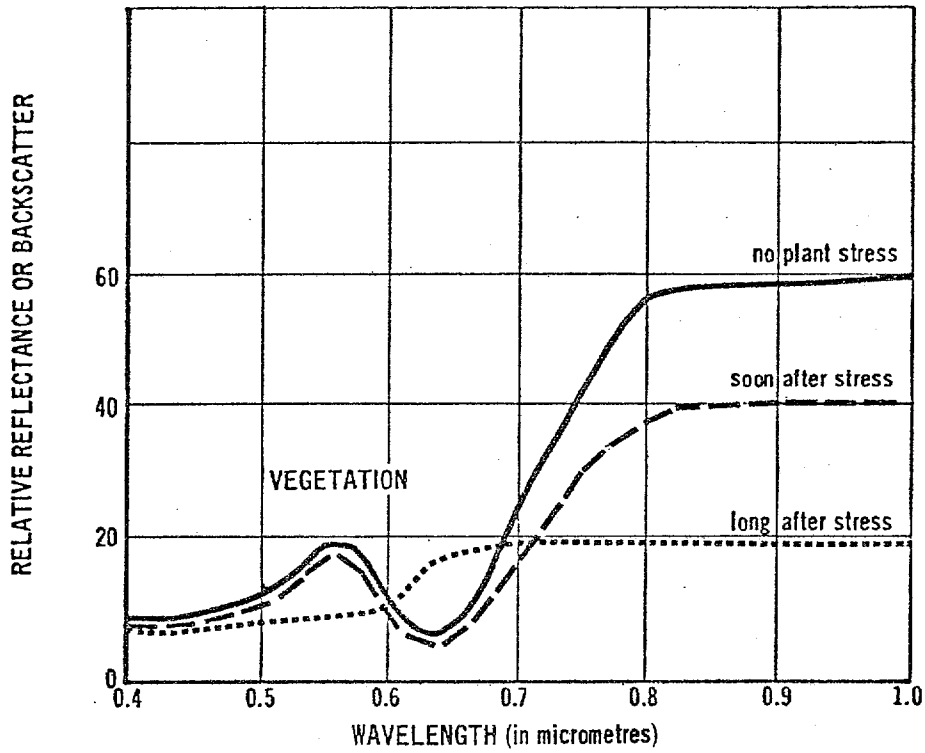


FIGURE 9: Spectral characteristics of vegetation showing decrease in infrared response because of stress. Data from Remote Sensing in Ecology, Philip L. Johnson Ed., 1969

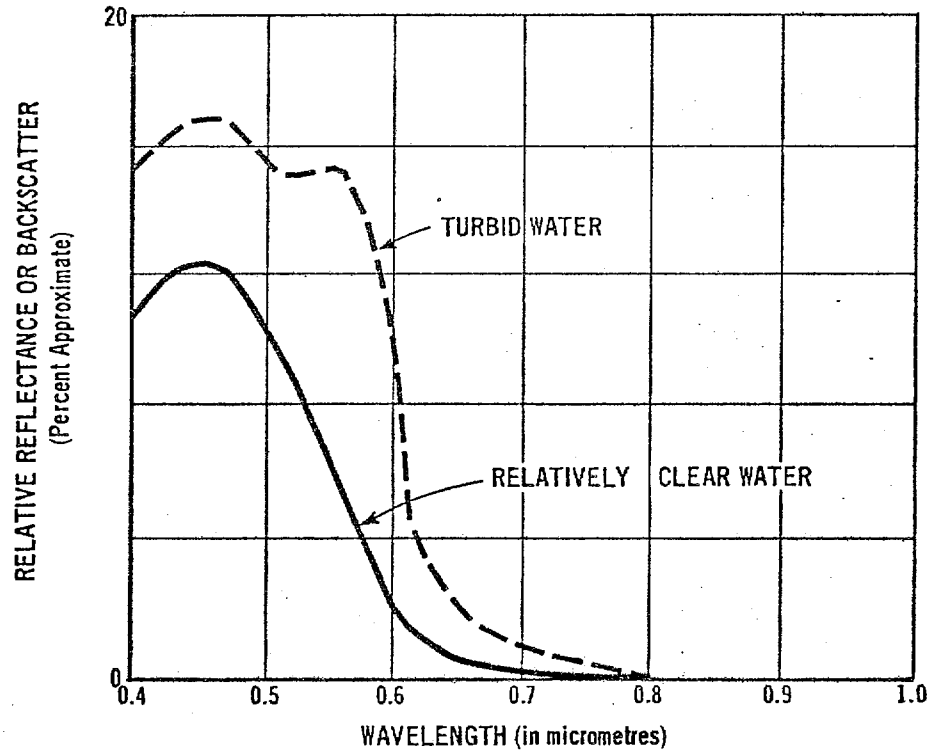


FIGURE 10: Spectral characteristics of backscattered EMR from water. Data from Polcyn and Lyzenga, 1973 and G. Moore personal communication.

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.

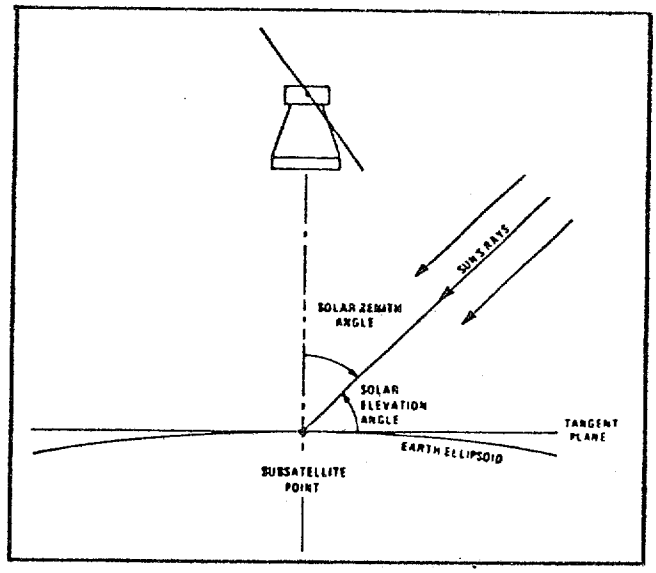


Figure 11: Solar Elevation Angle. Figure from NASA ERTS Data Users Handbook.

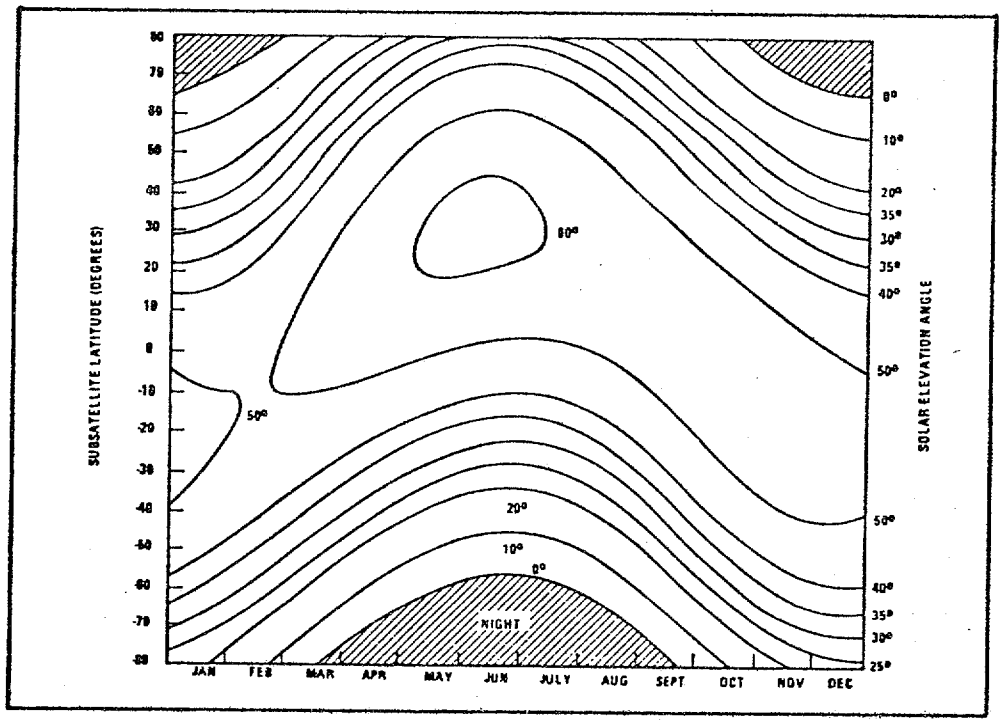


Figure 12: Solar elevation angle history for the Landsat Satellite System as a function of latitude. Satellite crosses equator at 9:42 AM (Descending Node). Figure from NASA Data Users Handbook.

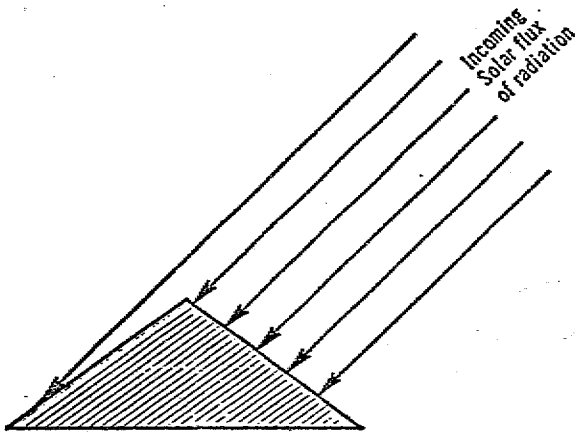


Figure 13: Incoming solar flux of radiation striking topography in slope. The slope facing the source of illumination receives four times the energy per unit area as the slope facing away.

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 32,930 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 that 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 radiometric elements 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) interpolating 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 perceived as white. Hue (magenta, purple, etc.), brightness (light blue vs dark blue, etc.) and saturation of 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. Drainage: Drainage patterns, drainage density (drainage texture), cross-sectional geometry of valleys and width of stream channels.

3. Cover types: 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

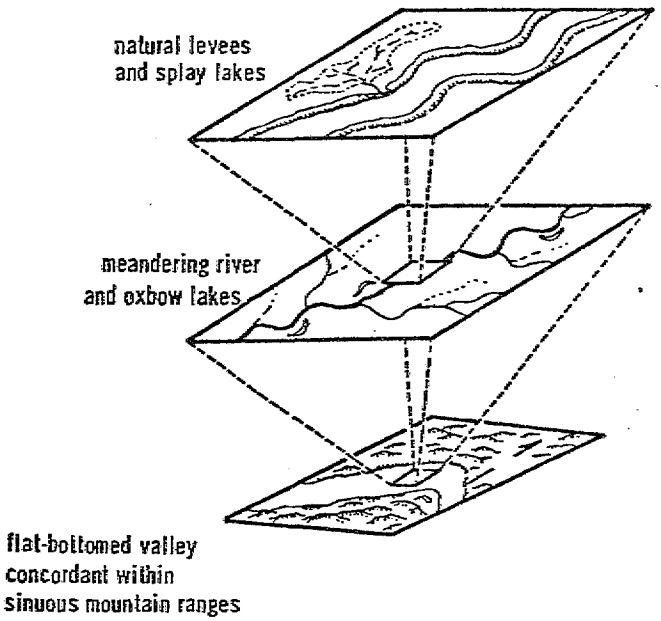
Analysis of remotely sensed data is accomplished through recognition of symmetrical distributions of image elements (tone, color; that is, data) displayed on imagery. These symmetrical distributions of the elements are referred to as patterns. Patterns are differentiated on the bases of their size, shape, 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.

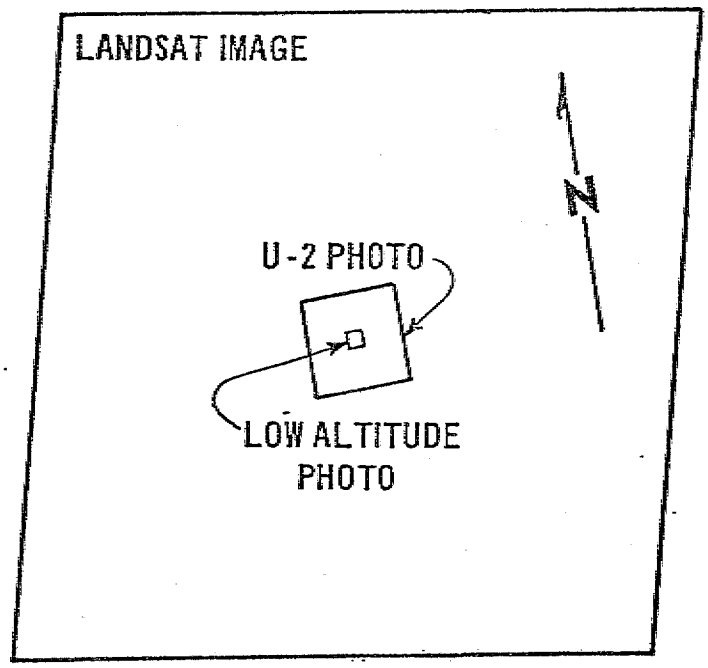
It is important to note that image scale has no bearing upon the "scale of analysis"; however, the dimensions of the image and the smallest image data element impose upper and lower limits, respectively, on the "scale of analysis". If a pattern on an image cannot be identified and cannot be subdivided 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



Standard black and white, low altitude aerial mapping photography
Format = 9 x 9 in. (22.9 x 22.9 cm)
Scale = 1 : 20,000 (1 in. = 1666 ft.)
Coverage = 7.2 sq. mi. (18.6 sq. km.)

Ultra high altitude (U-2) aerial reconnaissance photography
Format = 9 x 9 in. (22.9 x 22.9 cm)
Scale = 1:120,000 (1 in. = 10,000 ft.)
Coverage = 290 sq. mi. (742 sq. km.)

Landsat imagery
Format = 7.3 x 7.0 in. (18.5 x 17.8 cm)
Scale = 1:1,000,000 (1 in. = 83,300 ft. = 15.8 mi.)
Coverage = 12,500 sq. mi. (32,930 sq. km.)



COMPARATIVE AERIAL COVERAGE
OF IMAGERY TYPES

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 preconceived geological models in mind; this is because their geological experience and available ground data are 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 to eliminate 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 are 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

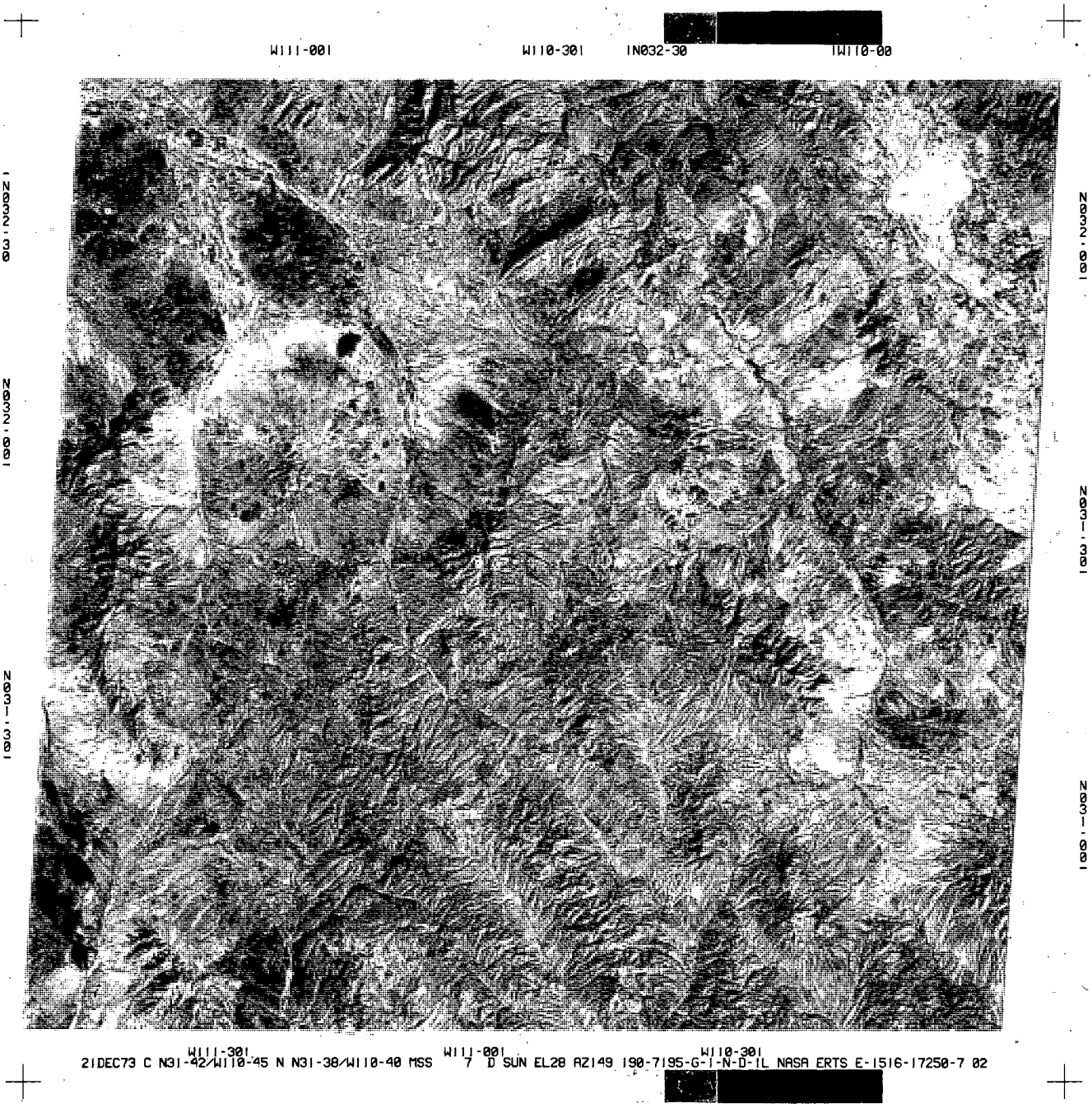


Figure 15: Landsat 1, band 7 (reflected solar infrared). Tucson, Arizona appears near the upper left corner and Wilcox Playa in the upper right. The image was acquired on December 21, 1973, under conditions of low sun angle illumination (28°). Note particularly lineaments, drainage patterns, and drainage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

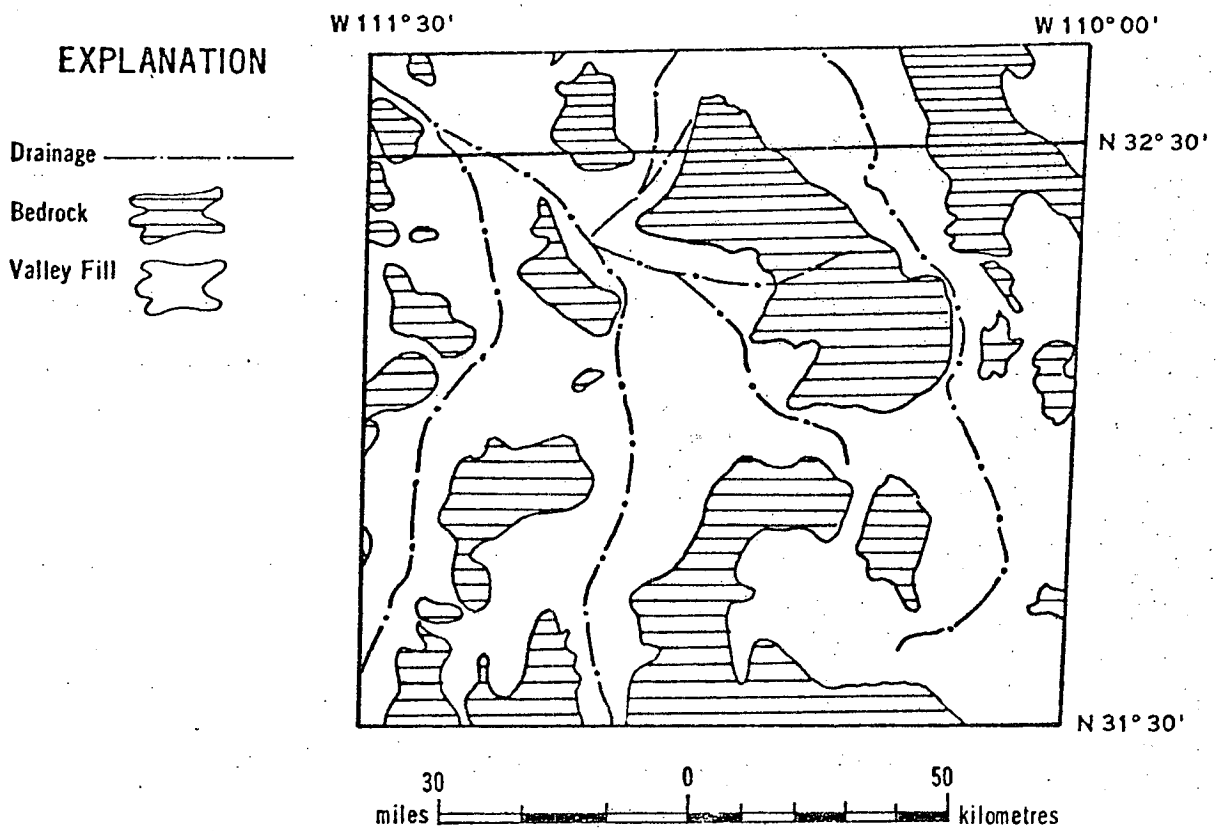


Figure 16: Image interpretation of bedrock areas, valley fill, and major stream drainage. From Landsat band 7 image, 1:1,000,000 scale. Date of image acquisition: December 21, 1973. Landsat image identification: E-1516-17250.

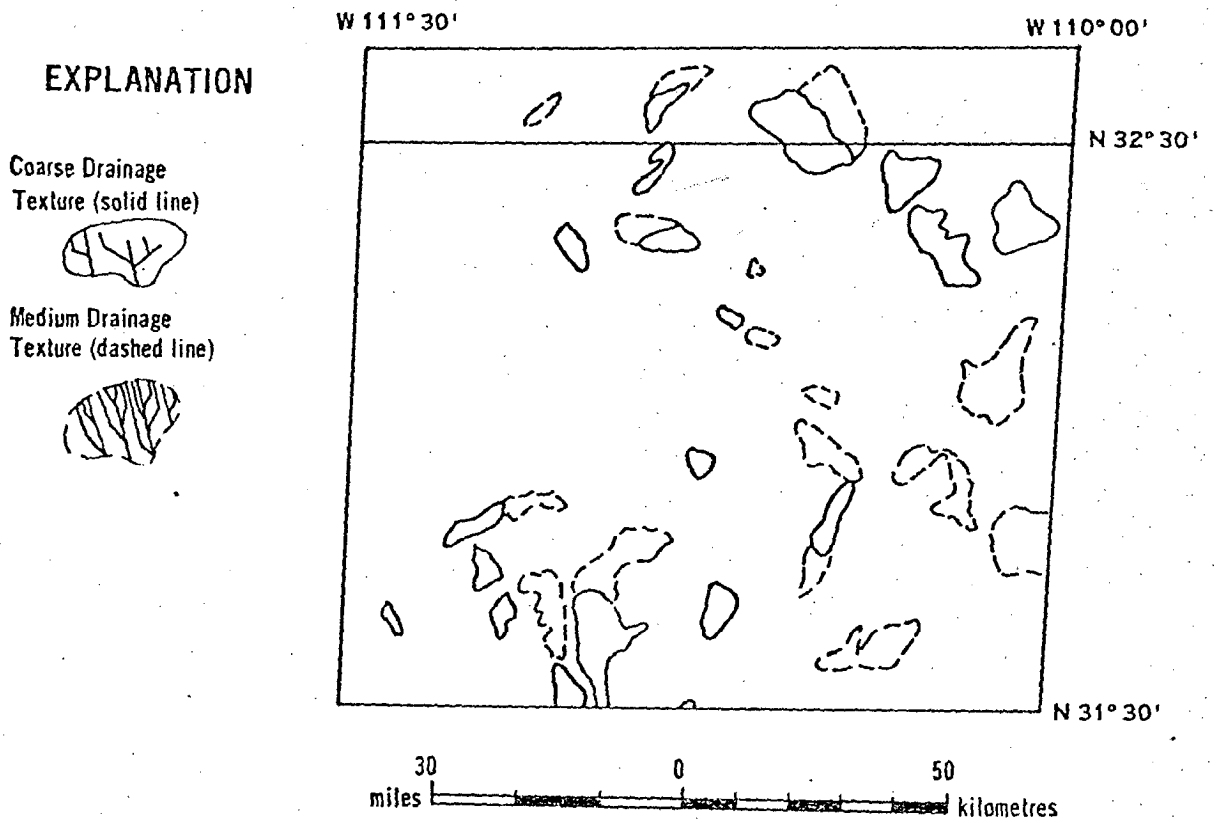


Figure 17: Image interpretation of drainage density (texture). From Landsat band 7, 1:1,000,000 scale. Date of image acquisition: December 21, 1973. Landsat image identification: E-1516-17250.

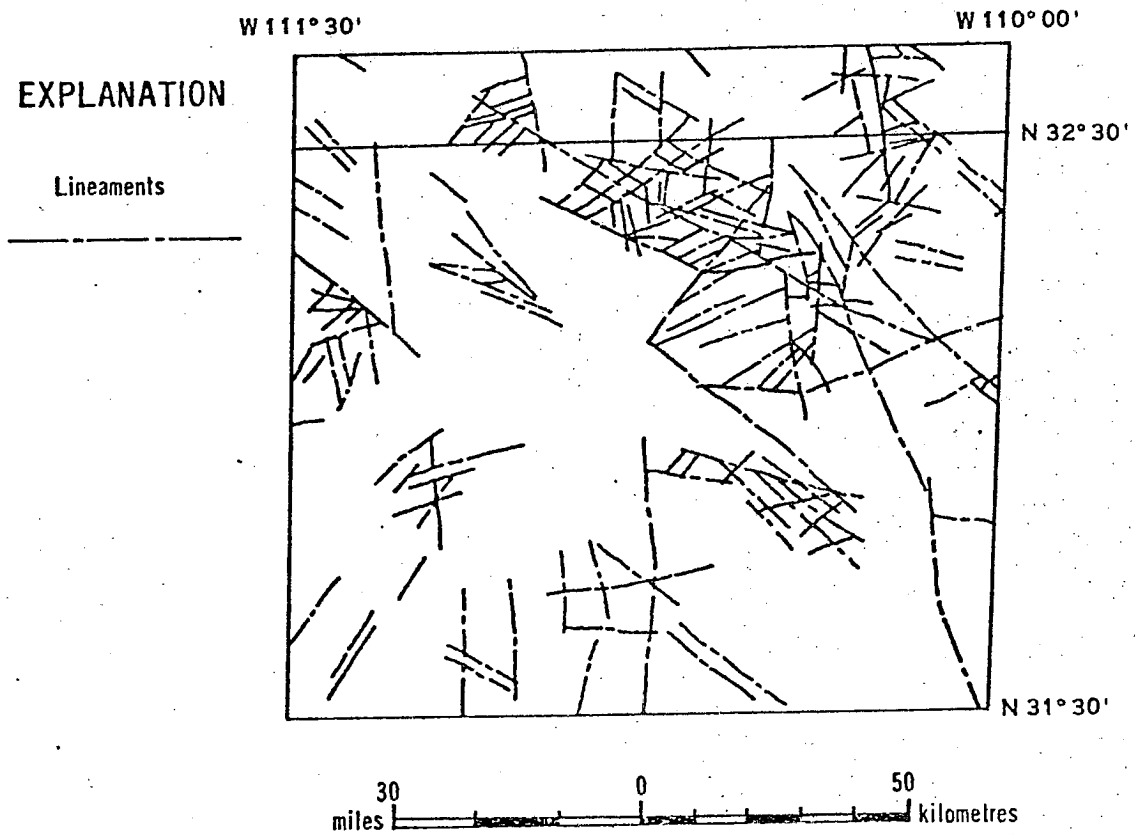


Figure 18: Image interpretation of lineaments in bedrock and adjacent valley fill. From Landsat band 7, 1:1,000,000 scale. Date of image acquisition: December 21, 1973. Landsat image identification: E-1516-17250.

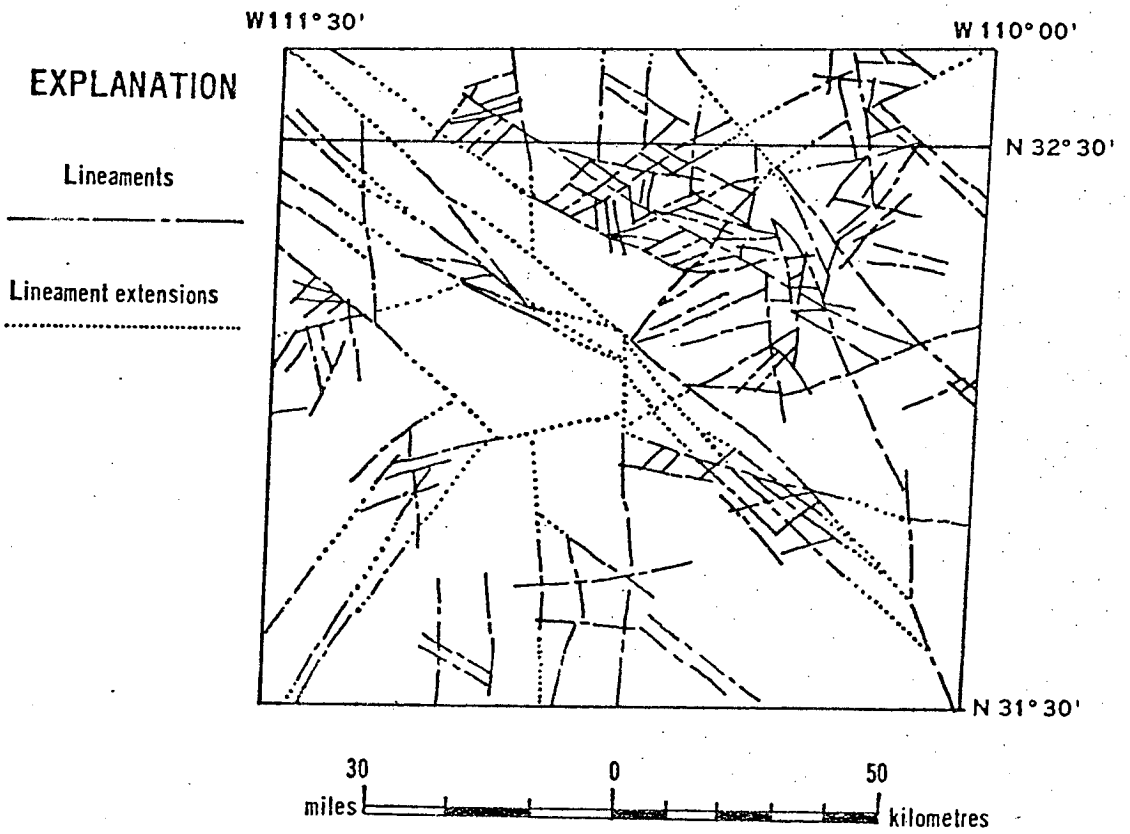


Figure 19: Interpretation of lineaments by extending lineaments into valley fill along trends. This is a geological interpretation of image information. From figure 18.

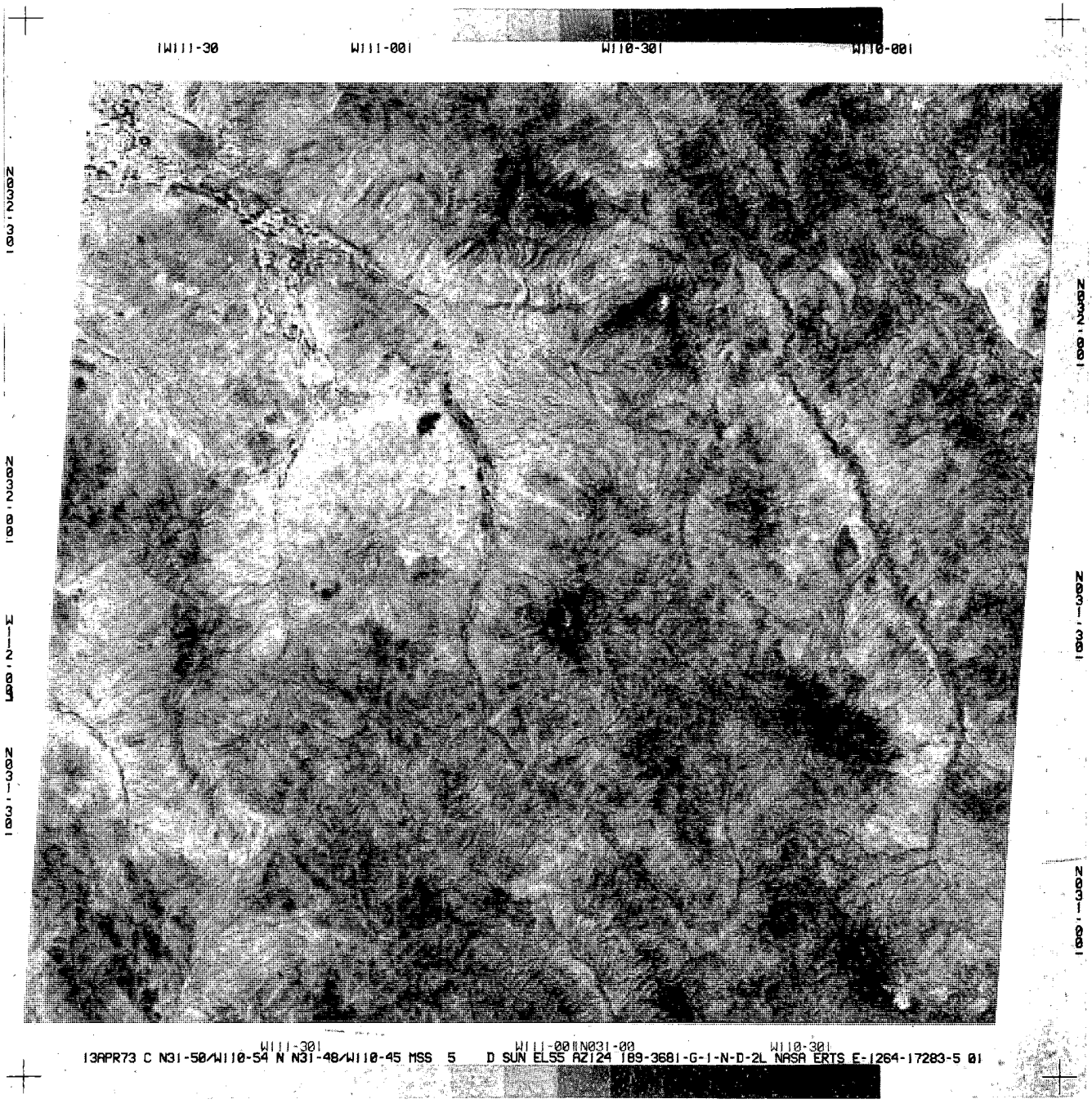


Figure 20: Landsat band 5 image of Tucson, Arizona. Date of acquisition: April 13, 1973. Image identification: E-1264-17283. Riparian vegetation shows as dark, sinuous lines in basin areas. Vegetation anomalies on alluvial fans show as darker toned patterns. Actual photo interpretation of vegetation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

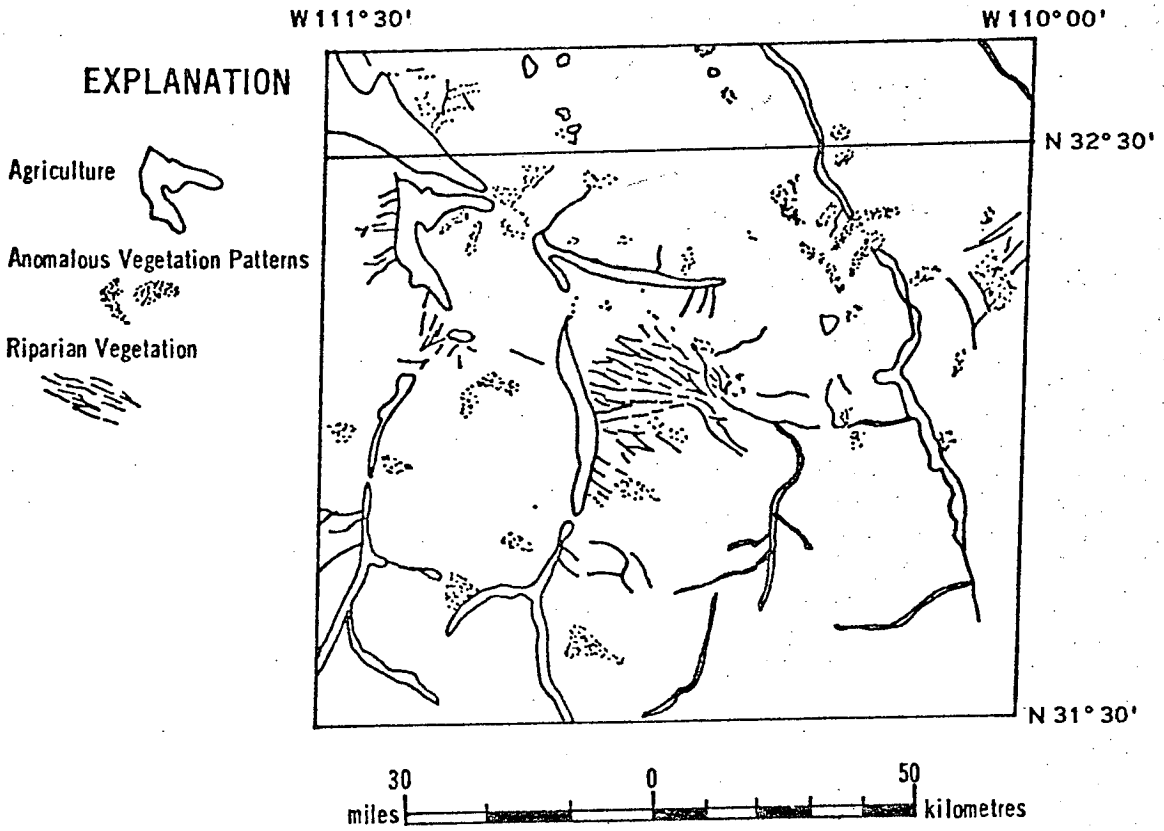


Figure 21: Image interpretation of vegetation patterns. From Landsat color composite, 1:1,000,000 scale. Date of image acquisition: April 13, 1973. Landsat image identification: E-1264-17283. Note: Figure 20, Landsat band 5 substituted for this image in this paper.

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. (See Osterkamp and Cooley, 1975)
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

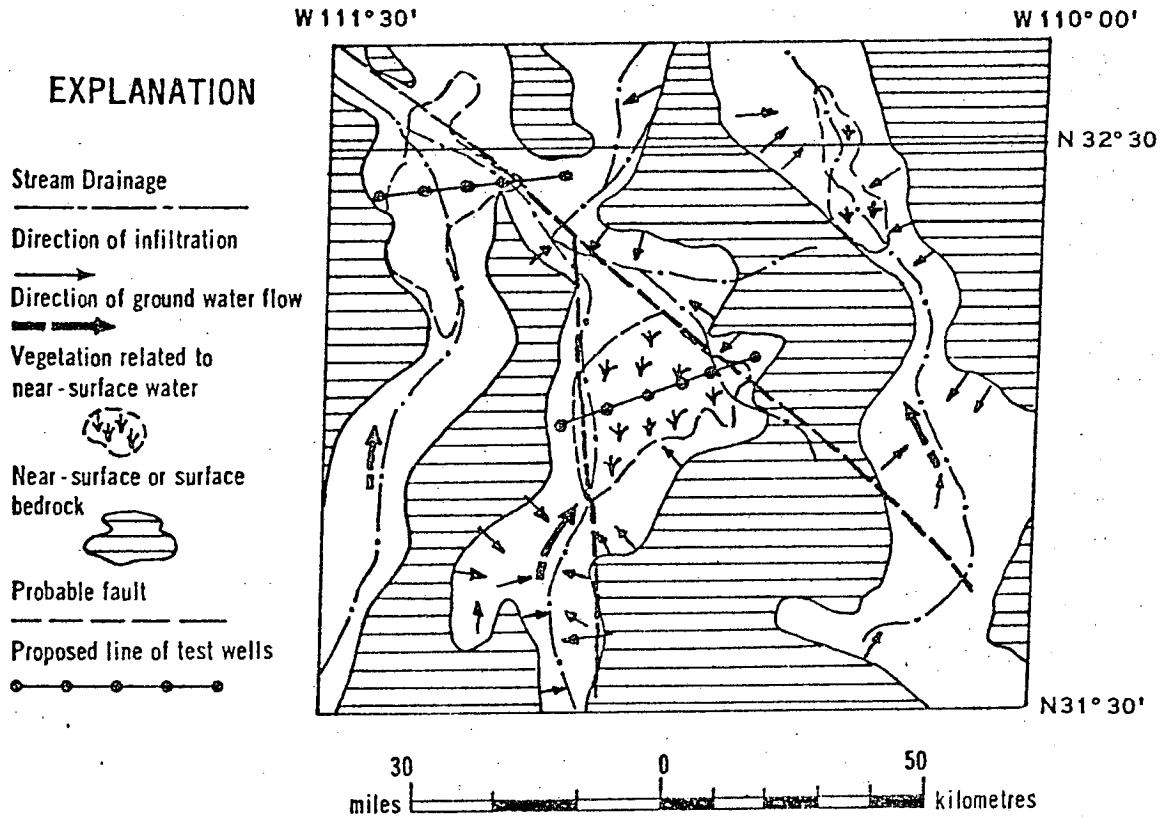


Figure 22: Geohydrologic interpretation of landscape patterns recognized on Landsat imagery. Interpreted from figures 16, 17, 19, and 21.

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 felsic 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 ruptural 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 formatting 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.

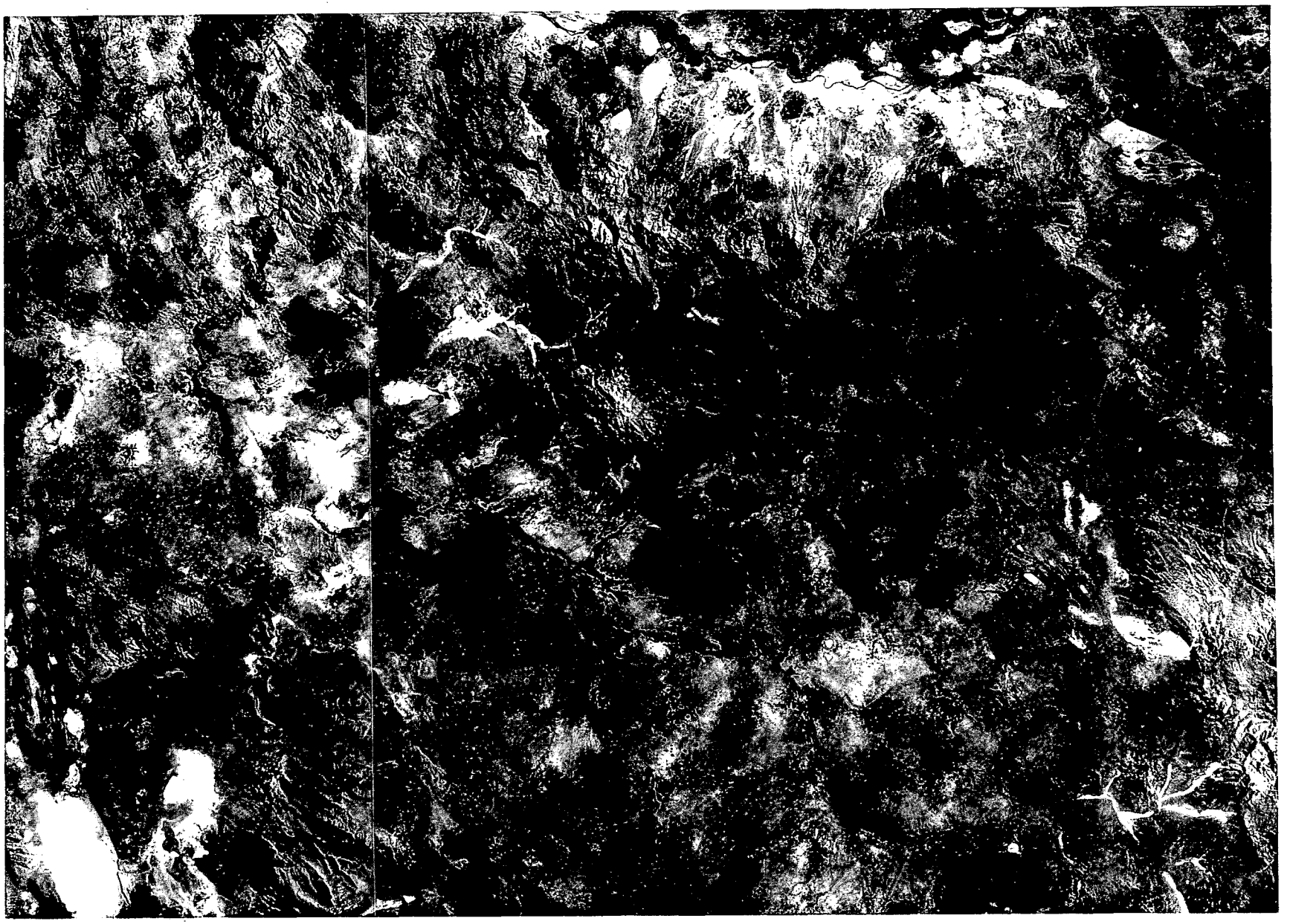


Figure 23: Overlapped Skylab photos, identification numbers G30A020315 and G30A020316. Major rivers displayed on the photos are the Snake (top center) and Owyhee (top left to lower right). The photos were taken in August, 1973 by Skylab astronauts.

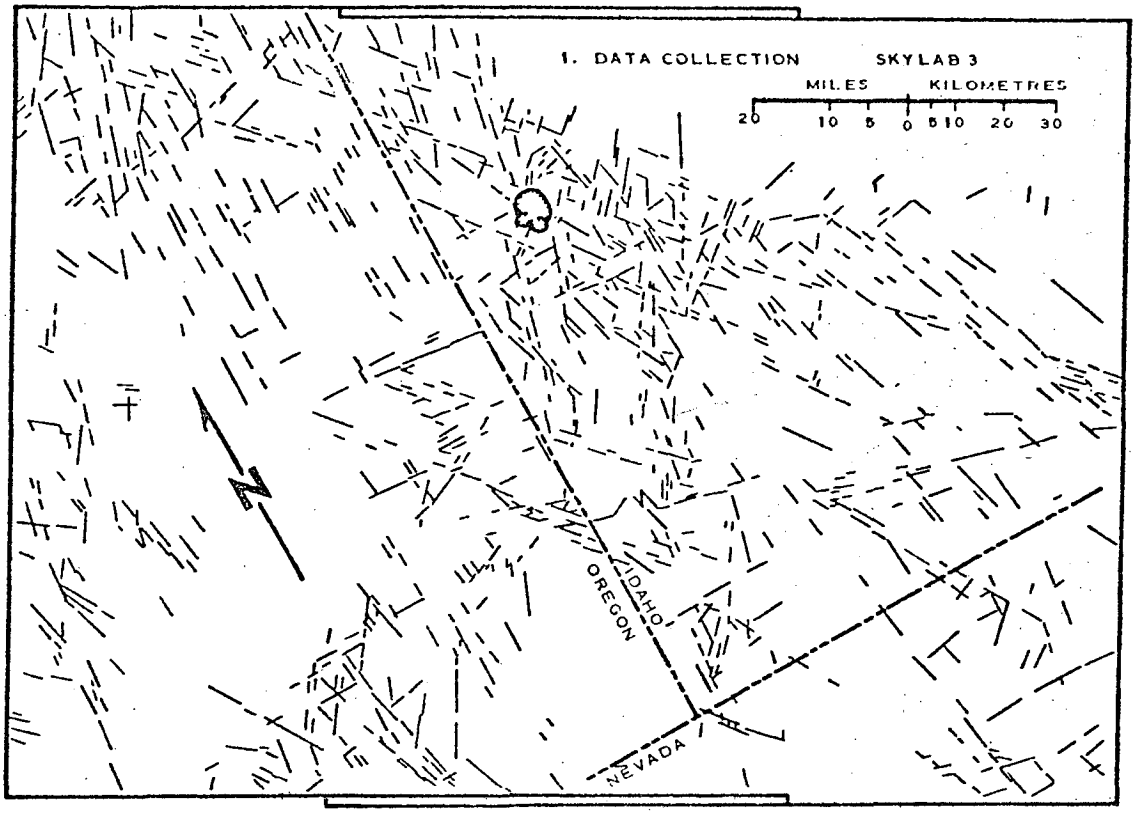


Figure 24: Caldera complex and associated linear structural elements.

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.

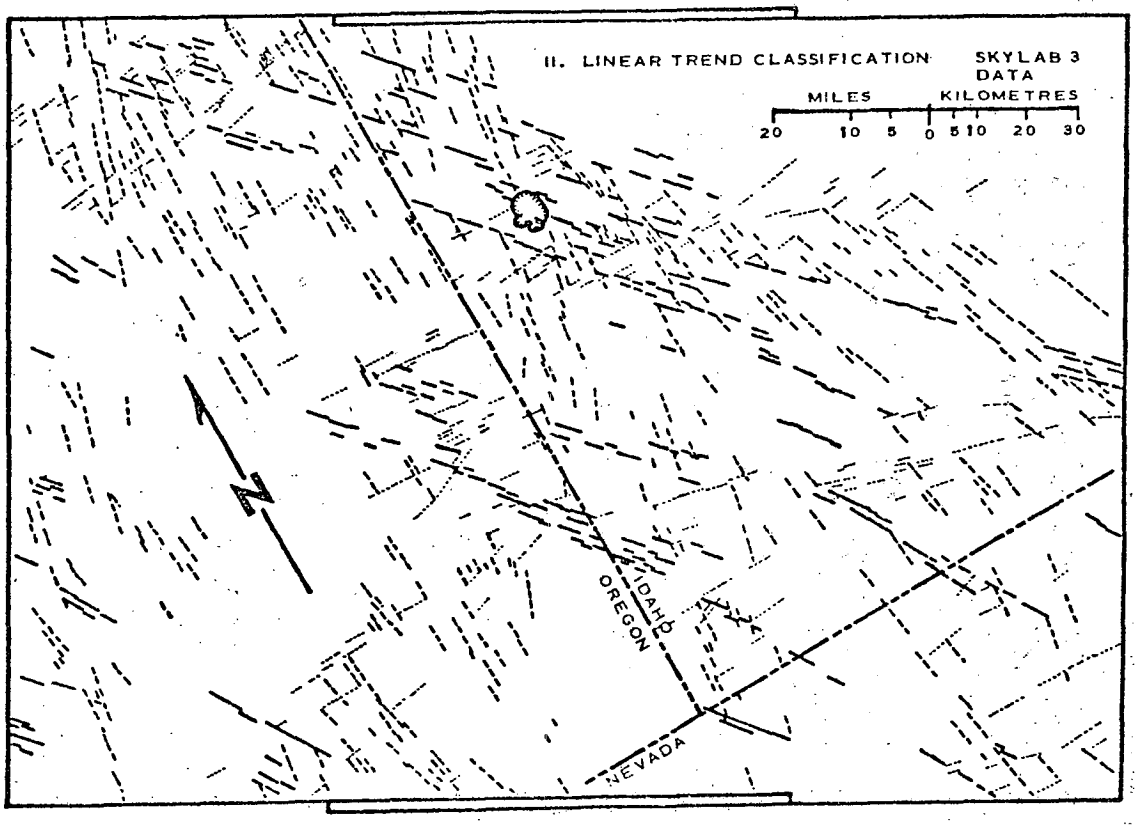


Figure 25: Accentuated major structural trends; N40W = heavy, N5W = medium, N85W = light.

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.

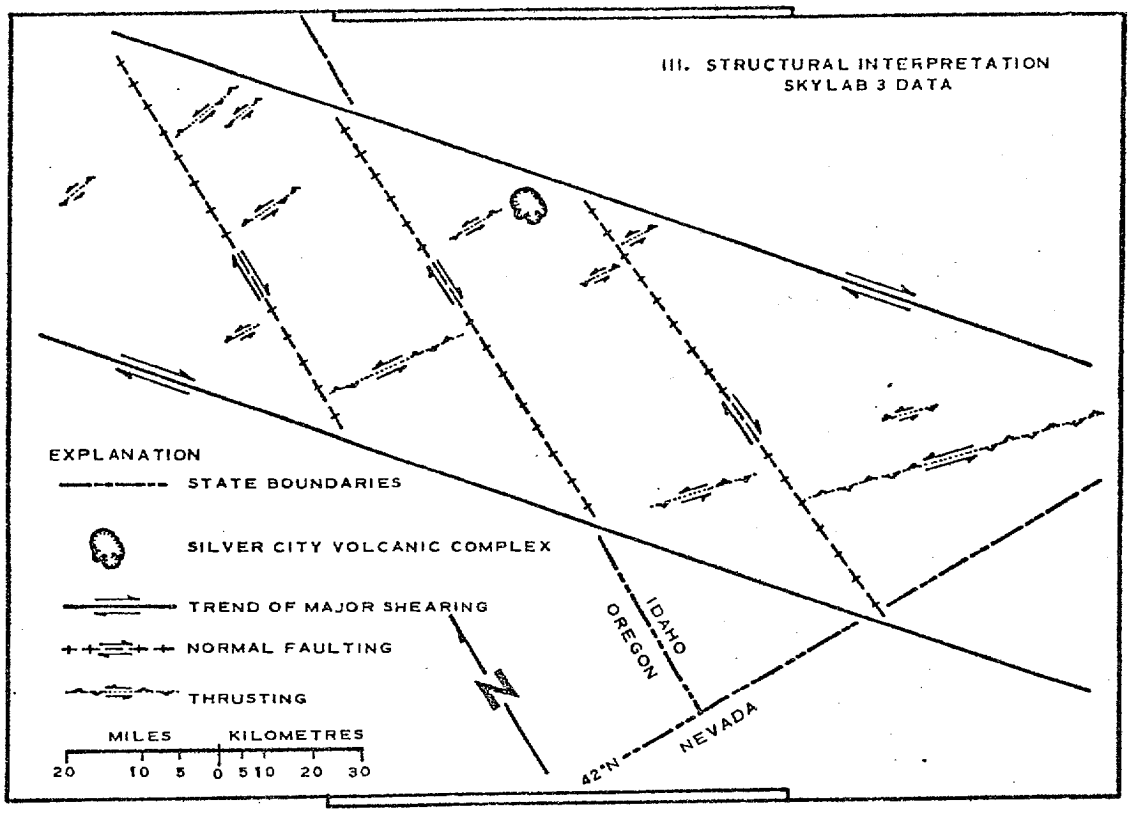


Figure 26: Simplified volcano-tectonic interpretation showing dominant movement directions along major zones of weakness.

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 HIZ
		N 0-43° W 90-80° 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, THRUS N 10° W GRABENS
-N 85° W LEFT-LATERAL THRUSTING		N 75° W 70-75° SW 26-30° SW	N 75-85° W HIZ S LOZ S	N 70-90° W HIZ
-N 40° E UNIDENTIFIED MINOR TREND	N 30-40° E	N 24-50° E 50-75° E	N 65° E	N 35-55° E HIZ N 67-75° E HIZ

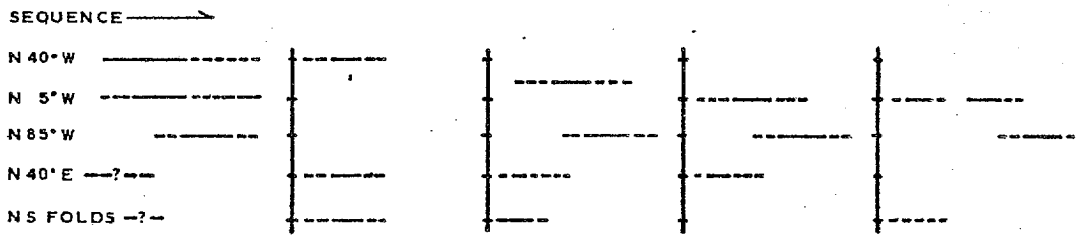


Figure 27: Correlation of interpreted fault geometries and documented field evidence.

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.

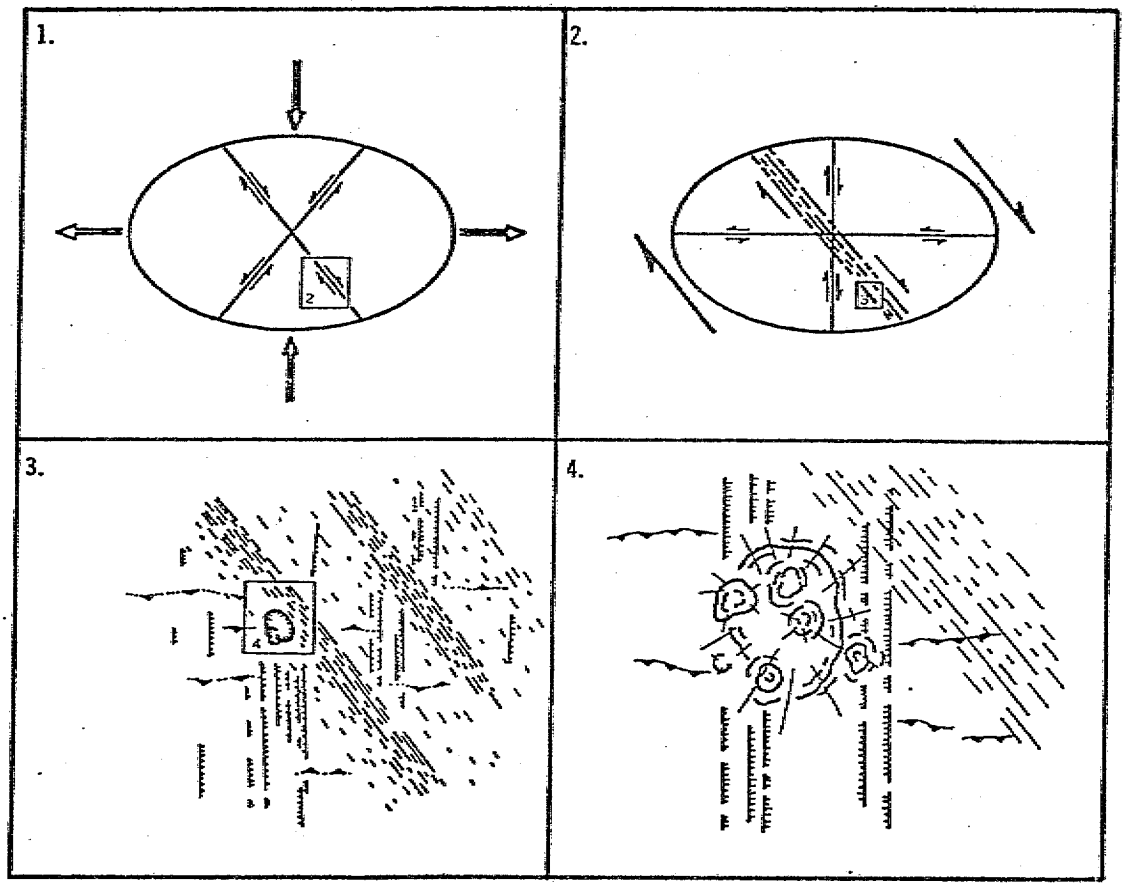


Figure 28: Synoptic geologic model of interpretations based on several scales of remotely sensed data analysis. (1) Small-scale regional pure shear system based on analysis of 1:5,000,000 scale Landsat band 7 mosaic of conterminous U.S.; (2) Large-scale regional simple shear system based on analysis 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 were 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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Osterkamp, W. R., and Cooley, M. E., 1975, (abs) Evidence for fracture permeability in the valley-fill deposits of the Tucson area, Arizona: A case history research conference, Univ. of Kansas, Feb. 18-20, 1975 Space Technology Center, p. 44.

Pansze, Arthur J., 1971, Geology and ore deposits of the Silver City--Delamar--Flint Region, Owyhee County, Idaho: unpublished PhD thesis, Colorado School of Mines, 151 p.

Polcyn, F. C., and Lyzenga, D. R., 1973, Multispectral sensing of water parameters in Thompson, K. P. B., and others, eds., Remote sensing and water resources management: Urbana, Ill., Am. Water Resources Assoc., p. 394-403.

Scherz, J. P., and Stevens, A. R., 1970, An introduction to remote sensing for environmental monitoring: Madison, Wisconsin, The University of Wisconsin, 80 p.

Sorenson, Robert E., 1927, The geology and ore deposits of the South Mountain Mining District, Owyhee County, Idaho: Idaho Bureau of Mines and Geology, Pamphlet 22, 49 p.

U.S. National Aeronautics and Space Administration, Goddard Space Flight Center, 1971, Data users handbook (for Earth Resources Technology Satellite): U.S. Natl. Aeronautics and Space Admin., Goddard Space Flight Center Doc. 71SD4249 (loose-leaf, variously paged).

U.S. National Aeronautics and Space Administration, Johnson Space Center, 1971, Skylab Earth resources data catalog: U.S. Natl. Aeronautics and Space Admin., Johnson Space Center Doc. JSC 09016, 359 p., with maps.

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.

Colwell, R. N., ed., 1960, Manual of photographic interpretation: Falls Church, Virginia, Am. Soc. Photogrammetry, 868 p.

Lueder, D. R., 1959, Aerial photographic interpretation: New York, McGraw-Hill Book Company, 462 p.

Miller, V. C., and Miller, C. F., 1961, Photogeology: New York, McGraw-Hill Book Company, 248 p.

Ray, R. G., 1960, Aerial photographs in geologic interpretation and mapping: U.S. Geol. Survey, Prof. Paper 373, 230 p.

Reeves, R. G., ed., 1975, Manual of remote-sensing: Falls Church, Virginia, Am. Soc. of Photogrammetry, 2144 p.

Von Bandat, W. F., 1962, Aerogeology: Houston, Texas, Gulf Publishing Co., 350 p.

Way, D. S., 1973, Terrain analysis: Stroudsburg, Pennsylvania, Dowden, Hutchinson, and Ross, Inc., 392 p.

Copy to → J D Sell ✓
G J Slatkis
⊛ please note

F. T. Graybeal

RECEIVED
JAN 10 1977
S. W. U. S. EXPL. DIV.

New York, January 5, 1977

F. T. G.
JAN 11 1977

MEMORANDUM FOR: All Managers
Exploration Department

LANDSAT Image Interpretation

Each of you will have now received one or more black and white LANDSAT images from Bryan Bailey. Please select one of these inquiries and assign it to a geologist for analysis and interpretation, and North American geologists selected for this work should phone me for more detailed instructions. ⊛

The results of each interpretation, which will in all cases be complete by March 1, should be posted on some type of clear film, in duplicate, and one copy should be mailed to Mr. Bailey. Mr. Collins, who will also have studied the images, will comment on the work and will meet with some of the geologists involved, probably in Salt Lake during March. During that meeting some determination of the benefit to the company of this type of work will be made, and orders placed for enhanced images. When the enhanced images arrive, they in turn will be interpreted, and Mr. Collins will compare the two interpretations, and try to determine the aggregate incremental benefit of the enhanced images over the black and white.

R. L. Brown

R. L. Brown

cc: JJCollins
GBBailey

ASARCO

Southwestern Exploration Division

December 27, 1976

TO: J. D. Sell
G. J. Stathis

FROM: F. T. Graybeal

LANDSAT STUDY

Please refer to paragraphs 2 and 3 of the attached letter by G. B. Bailey. I am asking that each of you study areas of the two photos with which you are particularly familiar to determine the applicability of this imagery. One photo covers the Phoenix-Globe-Tucson area (poor quality), the other covers Tucson-Wilcox-Cananea. I suggest that your attention be directed to less disturbed alteration zones such as Helvetia, Red Mtn., Sunnyside, Courtland-Gleeson, Ray-Christmas area, and northern Sonora areas.

Your findings along with significant aspects of other features you might see or wish to study should be completed by the end of the 1st quarter of 1977 and reported to me as briefly as possible. Please also comment on the applicability of LANDSAT imagery to porphyry exploration and whether or not further studies should be performed.

F. T. Graybeal

F. T. Graybeal

FTG:lb
Atts.

cc: WLKurtz - w/o atts.

F. T. G. F. T. G. ASARCO

DEC 0 1 1976 DEC 1 0 1976

Let me have this back when photographs came in

RECEIVED DEC 10 1976 S. W. U. S. EXPL. DIV.

December 7, 1976

Salt Lake Exploration Division

D. P. Cadwell
Manager

LANDSAT IMAGERY
INTERPRETATION AND
EVALUATION EXERCISE

MEMORANDUM FOR:

J. C. Balla	R. E. Gale
D. P. Cadwell	R. S. Gray
J. V. Desvaux	F. T. Graybeal
D. M. Fletcher	R. B. Sprague
J. H. G. Fuchter	S. Von Fay

Please find enclosed Band 5 or Band 7 1:1,000,000 scale LANDSAT images of areas within your respective regions. False color composite prints have been included for the scenes for which the color positive was already in existence. Being sent separately in a map tube are the complimentary Band 7 or Band 5 1:250,000 scale images of the same areas within your respective regions.

As you may recall, Mr. Osborne suggested in his Sept. 2 memo that some preliminary image enhancement from certain areas which he designated might help us evaluate the potential benefit to our exploration efforts from the use of enhanced LANDSAT imagery. At the suggestion of Mr. Collins, it was decided that an important preliminary step would be the examination and interpretation of standard LANDSAT imagery to serve as a frame of reference for our evaluation of the enhanced imagery. Thus, the distribution of the enclosed images is the first step in this enhanced imagery evaluation exercise. It is hoped that the exercise will evolve generally as follows. Between now and late winter or early spring (Northern Hemisphere) we would like the exploration geologists most familiar with the areas involved to study and interpret, in as much detail as possible, the geology represented on the various images, particularly as it relates to the occurrence of known mineralization and to the exploration for unknown mineralization. In the near future I will be circulating some information and references which should be helpful in the interpretation of this imagery. *

In addition to the evaluation of enhanced imagery and its value to exploration, it is hoped that this exercise will serve to help us all become more

aware of what satellite imagery, in general, has to offer the exploration geologist and what its shortcomings are. Therefore, it is the present plan to organize a meeting to be held at the end of this interpretation period and to be attended by as many of those geologists who were involved in the imagery studies as possible. The purpose of the meeting will be to exchange ideas, techniques, and results which have evolved from the exercise in an effort to better evaluate what the role of satellite imagery should be in an integrated mineral exploration program. During the interpretation period, Mr. Collins will be studying imagery from several of the same scenes that many of us will be studying and will thus be in a good position to act as referee for this exercise. In addition, an important function of the post-interpretation meeting will be to select those scenes which will be enhanced and then re-interpreted. *

In anticipation of certain questions which will likely arise concerning the imagery which is being distributed, let me make a few comments.

1) The areas of coverage were selected generally in two ways: a) by the designated offices in response to Mr. Osborne's Sept. 2 memo, and b) by Mr. Collins in an effort to include imagery from a variety of geologic settings and from areas of current or potential exploration interest.

2) The precise scenes covering these areas were selected by me using certain limiting criteria. Mr. Collins and I initially designated presumed optimum seasonal periods based on best chance for snow-free coverage and for optimum moisture contrast for some of the areas involved. For other areas no seasonal constraints were applied. Next, quality and cloud cover data for all scenes available for each area within the applied seasonal constraints were examined. The scene selected for each area was that scene which exhibited the best image quality and least cloud cover for the spectral bands desired. For most scenes this was a quality designation of 8 (the highest rating) & 0 cloud cover. Some areas, notably Ireland and New Zealand, did not have coverage with zero percent cloud cover. With 2 or 3 exceptions, the quality of the images does appear to be quite good. It must be remembered that the apparent quality deteriorates some during the enlargement process. The horizontal "striping" is inherent in the present data acquisition and treatment process.

3) Regarding the spectral bands selected, the general consensus from a number of knowledgeable sources was that Bands 5 and 7 provided the most data applicable to geologic interpretations. Band 5 was thought to be optimum in areas of good rock exposure because of better chance for distinguishing between certain rock types. Band 7 was said to be better in areas of high vegetation cover because an increased ability to delineate structural features. In general, band selection was made using these criteria. The presumed optimum band was selected for the 1:250,000 scale image of each area, and as a trade off, the complimentary band was selected

for the 1:000,000 scale image of that area. In a few cases where a number of images were required to cover a designated area, band selection for the two image scales was alternated.

After a cursory examination of the images, it appears to me that in a few cases the complimentary band to the one selected for the enlarged image may prove to be more beneficial. If during the course of your studies you find this to be the case, I can obtain that complimentary band for you in fairly short order.

As noted earlier, I will soon be sending some information and references which will hopefully aid in the study and interpretation of this imagery. If I can be of additional assistance to you in regards to this exercise, please do not hesitate to contact me.

Bryan Bailey

G. BRYAN BAILEY

GBB/mb
Enc.

cc: TCOsborne/RLBrown
JHCourtright/WLKurtz
JJCollins

Fred,

Thank you for the valuable assistance with this NASA thing — I really do appreciate it! As I indicated on the phone today your imagery will be sent next week. Thanks again!

Regards,
Bryan

1/4/77

FROM: F. T. GRAYBEAL

TO: G J Stathis LANDSAT

GB Bailey will order large color photo Yerington area; send directly to you - should be in 3 weeks or so.

Dick Brown now wants to get one enhanced picture for each office after review of color composites, so you and JDS will have to decide which of the 3 we will have ~~so~~ is best candidate to be enhanced.

copy JDS ✓

Circulate to geologists

F. T. Graybeal

F. T. G.

JAN 11 1977

RECEIVED

JAN 10 1977

S. W. U. S. EXPL. DIV.

New York, January 5, 1977

MEMORANDUM TO: All Managers
Exploration Department

Remote Sensing

The attached material is sent to you in an effort to inform each of the geologists on your staff about recent remote sensing technology advances and data utilization techniques.

The individual items in the enclosure cover a number of unrelated subjects, as they were simply pulled from a file which has grown during the past four months. Study of the material, should however, bring the reader pretty well up-to-date on this subject.

Please circulate this mailing to your staff.

R. L. Brown

R. L. Brown

Attachment

T. C. O.

DEC 7 1976

December 7, 1976

Dr. Arthur A. Brant
Newport Exploration Ltd.
44 Briar Ridge Road
Danbury, Connecticut 06610

Dear Dr. Brant:

Some time ago, I learned that Sam Pickering, the State Geologist of Georgia, is a skillful user of LANDSAT data, and shortly thereafter John Collins, who works with me on LANDSAT-GEOSAT matters, had an opportunity to spend a few hours with him.

Mr. Collins reported to me on his visit in the attached letter, which I forward as it is of interest.

You will note that Mr. Pickering is not enthusiastic about GEOSAT.

Very truly yours,

R. L. Brown

Attachment

121 Wettaw Lane, No. 217
North Palm Beach, FL 33408
305-842-6380 845-0375

RECEIVED
NOV 29 1976
EXPLORATION DEPT.

R.L.B.

DEC 6 1976

November 24, 1976

Mr. R. L. Brown
Assistant Director of Exploration
ASARCO Inc., NYO

Dear Mr. Brown:

In accordance with your request, relayed to me by Bryan Bailey, I visited Sam Pickering, State Geologist of Georgia, on Monday the 22nd, and was impressed by his practical usage of Landsat imagery. I have telephoned the gist of it to Bryan. Attached is a copy of the manuscript of a talk Pickering gave recently on this subject.

Lacking in the script is mention of more recent discoveries of six new ilmenite beach sand deposits attributable partly to Landsat. Also omitted is the Landsat revelation that the gold mines in a major shear zone are localized on heretofore unseen cross fractures. However, he does not expect remote sensing will reveal ore deposits directly, nor in Georgia allow the direct identification of rocks and alteration. He is a firm believer in coordinating field work with Landsat and photo interpretations and all his staff use the combination routinely.

The Georgia Survey has a standing order for all new cloud-free band 5 and 7 imagery in the form of 2.2 inch negatives from which they print their own enlargements or have a commercial firm do them. The reason is variations in the negatives and the poor quality of printing done by EROS at Sioux Falls. By comparison the EROS prints are a waste of money. Furthermore Pickering's $400 enlarger-printer can enlarge to 1:50,000 scale from the 2.2 inch transparency.

He demonstrated to me my error in thinking soil moisture would be critical in revealing structure in the Appalachians. In fact it is the sun angle; the longer the shadow the better. Since the time of day of each frame is always the same, the season controls, and December 21st is the optimum day. He demonstrated that even three months away much of the structural detail is lost.

RLB 11/24/76

Pickering is satisfied with his usage of Landsat and suspects that GEOSAT would be a waste of money. Also he agrees with me that the Defense Dept. probably has remote sensors in operation with all the precision that GEOSAT could wish. The problem is to get the product out of the Pentagon, and by-passing the secret equipment. As an illustration he showed me a photo interpretation map of the region around Atlanta with 62 vegetation and culture categories. This came from the Air Force, not NASA. He said it took a lot of effort, but the lesson is that if one State can do it, your Committee ought to be able to penetrate the Pentagon also.

I had expected perhaps a one hour interview but he talked for three hours and we had lunch as well. I suggest he would be an excellent consultant to your committee in view of his practical experience. Note, however, that the State would not pay any travel expenses and you might have to compensate the State for his time. Incidentally Sam cited Floyd Sabin ofChevron Oil as being expert in the use of Landsat. Perhaps he is already on your Committee.

Sincerely yours,

John J. Collins

John J. Collins

CC: GBBailey

157-19.2

ASARCO Incorporated
Salt Lake Exploration Division

RECEIVED
OCT 20 1976
EXPLORATION DEPT.

R.L.B.
OCT 19 1976

October 18, 1976

T. C. O.
NOV 3 1976

T. C. O.
NOV 8 1976

Mr. R. L. Brown
New York Office

Report on the Workshop
on Computer Analysis of
LANDSAT Data for Natural
Resource Applications

Dear Mr. Brown:

The following is a report on the Penn State University Workshop on Computer Analysis of LANDSAT Data for Natural Resource Applications which M. P. Barnes and I attended from September 30 through October 2, 1976. You have received from Dr. Barnes his report on the Workshop in which he ably describes the structure of the workshop and summarizes the sequence of computer analysis (and programs) which comprises the method of computer analysis of LANDSAT data employed by the Office for Remote Sensing of Earth Resources (ORSER) at Penn State. I will therefore not attempt to discuss in detail the points covered in Barnes' report. I am, however, also enclosing as a part of this report a copy of the ORSER-SSEL Technical Report 9-74 which contains an excellent step-by-step synopsis of the procedure we physically followed in learing how to use the ORSER method of LANDSAT data analysis. This "hand-on" learning process occupied approximately half of the workshop time, and related lectures and demonstrations took up the rest of the time. The LANDSAT data which we analyzed were part of a scene from Saudi Arabia. We followed the process described in Technical Report 9-74 up to but not including outputting of an LMAP. I have the computer output for the steps that we performed and will review them with John Collins in Denver tomorrow. Unless you are especially interested, I will not send this bulky output to you since you can see the general format of the various outputs in Technical Report 9-74. The last day of the workshop we saw a demonstration of an image display of the computer treated data. This process is essentially the same as that used to visually display color composite ratios of LANDSAT data, but rather than assigning different colors to certain ratios (e.g. 4/5, 5/6, 6/7) the colors are apparently assigned to the various spectral classifications identified by the computer analysis process. As with the ratioing technique the output can be displayed on a color T.V. monitor (as in our demonstration)

or printed on paper as a false color image. The argument put forth as the advantages of this process over those of ratioing is that ORSER method makes use of more of the pertinent data than does ratioing and results in less ambiguity during interpretation than ratioing.

The question which I think is the most important to Asarco and the one which I wish to address is: "Is this ORSER data analysis and image enhancement process one which Asarco should attempt to implement as an aid in exploration?" I believe that at the present time the answer to that question is "No". However, some explanation is in order. I believe that the ORSER process is a powerful tool for data analysis and image enhancement and could be at least in part implemented without prohibitive cost. For example, ORSER will sell their package of software for $700 which would allow us, assuming access to an IBM 370, Model 168 computer, to routinely output the data maps described in Technical Paper 9-74. However, as such, I do not believe these computer generated, character maps are a type of output which would be routinely used by most exploration geologists even though the maps can be printed at very usable scales. Rather, most field geologists, I think, would prefer to work with actual images; they perhaps would use the character maps to supplement their interpretation of the images, but having the imagery would be important. To provide, in house, images of the computer analyzed data we would be looking at an initial investment of between $50,000 and $150,000 in addition to financing the operation of the equipment. While I know of no commercial group currently offering data analysis and imagery enhancement using the ORSER process, it may be possible to do the computer analysis of the data in house and then have the imagery created by an outfit such as Geo Images.

In any event, we are talking about a significant investment for a product which for our purposes is currently not significantly better than color composite ratio enhancement. One reason the process and products are not presently available on the market is that their application and value to geologic disciplines are still being evaluated on a research level. It seems likely that when more and better spectral data are available from the satellite systems which will fly in the future the ORSER type of data processing and image enhancement will have the capability of providing significantly better enhanced imagery. It is my opinion that rather than becoming actively involved with trying to use an ORSER-type process at this time we should proceed with the experiments we have outlined to determine if we are interested in using enhanced imagery at all. At the same time we should closely follow the progress of the state of the art of the ORSER-type approach to LANDSAT data analysis and imagery enhancement so that we have proper knowledge to determine if this type of approach is one which we may want to try in the future.

Very truly yours,

Bryan Bailey

G. BRYAN BAILEY

GBB/mb
Enc.

cc: J.J.Collins
M.P.Barnes

ASARCO

RECEIVED
SEP 24 1976
EXPLORATION DEPT.

Northwestern Exploration Division
John C. Balla
Manager

R.L.B.
SEP 24 1976

September 21, 1976

T. C. O.
SEP 24 1976

Mr. T.C. Osborne, Director
Exploration Department
ASARCO Incorporated
120 Broadway
New York, New York 10005

Landsat
Imagery Enhancement

Dear Sir:

In response to your memorandum of September 2, we will be selecting a couple of areas in Alaska for Mr. Bailey to obtain the imagery, as soon as Mr. Appelgate returns from Alaska.

Although this may be a worthwhile experiment, I call your attention to Kennecott Copper Corporation's 1975 Annual Report, page 20 (copy attached) in which it is mentioned that Kennecott did a research program on satellite imagery for porphyry copper deposits for NASA, with negative results. I suggest that we contact NASA to see if this research project is available to us for study.

Yours very truly,

John C Balla

John C. Balla

JCB/mc

Attachment

cc: WLKurtz with attachment

R.L.B.
SEP 8 1976

6350 West Mansfield Ave., #55
Denver, Colorado 80235
303-989-0827

September 5, 1976

RECEIVED
SEP 8 1976
EXPLORATION DEPT.

Mr. R. L. Brown
Assistant Director
Exploration Dept.
ASARCO Inc., NYO

Dear Mr. Brown:

GEOSAT

Although not on the AIME program, Fred Henderson did secure a meeting room for Friday afternoon but for lack of publicity attracted only a couple of dozen. He had cornered me the day before.

Tony Barker outlined the sub-committees and said the program consisted of learning what could and should be done. Leo Miller said that existing Landsat imagery had improved his company's effectiveness by 10%. He also said that he did not expect that GEOSAT would reveal any ore directly but he did expect it to improve the quality and quantity of regional mapping.

When the discussion became general, I hazarded a guess that military satellites have sensors so sensitive they could do our work better than we can imagine, furthermore, the Military Geology Unit of the USGS may be using this imagery now. If confined to the USA, they might be allowed to compile a new set of maps along the lines Leo Miller mentioned. Henderson said he would look into it. General endorsement was given to my observation that interpretation of GEOSAT results would be the crucial thing.

The previous afternoon Henderson introduced me to Tom Melrose of Bethlehem Steel who has the task of finding a replacement for Halbouty, who cannot spare enough time. Later I elicited from Henderson that he would like to be appointed Managing Director since he knows more about the subject than anyone we have. It seems to me that if that takes place, we would not need a Chairman immediately, because some available member of the Board of Directors could act as spokesman for Industry.

The next GEOSAT meeting is scheduled for September 29th during the Mining Congress meeting in Denver. If you think well of the idea, Henderson would appreciate your nominating him as a full-time Managing Director. I recommend him to you.

Sincerely yours,

John J. Collins

John J. Collins

9/1/76

To - T.C. Osborne
From - G.B. Bailey

This is another example of the type of meeting that I referred to in my memo to you of August 30 which has some distinct potential for significantly advancing our knowledge of disciplines relating to LANDSAT. This particular workshop would appear to be of particular value if we were to become involved in working with enhanced LANDSAT imagery and wished to do at least initial image (tape) computer processing in house (through Barnes Associates?) rather than through a separate private contractor.

RECEIVED
SEP 8 1976
EXPLORATION DEPT.

GBB

RECEIVED
SEP 3 1976
EXPLORATION DEPT.

INTERIM NASA PAYLOAD MODEL FOR PLANNING PURPOSES

8 MAR 1976

	FY 76	FY 77	FY 78	FY 79	FY 80	FY 81	FY 82	FY 83	FY 84	FY 85	LAUNCH SITE	VEHICLE CLASS
SCIENCE (OSS)												
EXPLORERS & PATHFINDERS												
EXPL VEHS *	▽▽▽	▽	▽ ▽	▽	▽ ▽	▽ ▽	▽ ▽	▽ ▽	▽ ▽	▽ ▽	ETR/WTR	DELTA
SOLAR MAX MISSION (SMM)					▽		†	▽	†	▽	ETR	DELTA
HEAO		▽	▽		▽						ETR	ATLAS/CENT
HEAO II/III									▽	▽ ▽	ETR	
SPACE TELESCOPE								▽			ETR	
GRAVITY PROBE B							▽	▽			ETR	
OUT OF ECLIPTIC ODSSEY									▽		ETR	
LARGE SOLAR OBSRV										▽	ETR	
SPACELAB * DEDICATED P/L'S					▽	▽	▽2X	▽4X	▽8X	▽10X	ETR/WTR	
PARTIAL P/L'S						5	3	5	4	4	ETR/WTR	
LIFE SCIENCE												
VESTIBULAR FUNCT RESCH						▽					ETR	
BIOS (BIO ENGR SCI SAT)							▽ † ▽	† ▽	† ▽ †	▽ † ▽	ETR	
SPACELAB * DEDICATED P/L'S						▽	▽ ▽	▽ ▽	▽ ▽ ▽	▽ ▽ ▽	ETR/WTR	
PARTIAL P/L'S					2	3	3	4	2	2	ETR/WTR	
PLANETARY												
MARINER JUPITER SATURN		▽▽									ETR	TITAN/CENT
PIONEER VENUS			▽▽								ETR	ATLAS/CENT
PIONEER JUPITER ORB PROBE							▽				ETR	
PIONEER SAT/URAN TITAN PROBE								▽	▽	▽	ETR	
JUPITER SWINGBY OBOE							▽				ETR	
LUNAR POLAR ORBITER							▽				ETR	
VENUS ORB IMAG RADAR								▽			ETR	
MARINER MERC ORB								▽			ETR	
MARS POLAR ORBITER									▽		ETR	
HALLEY FLYBY										▽	ETR	
MARINER JUPITER ORBITER										▽	ETR	
TECHNOLOGY (OAST)												
SPHINX						▽					ETR	
LONG DUR EXP FAC					▽	†	▽ †		▽ †			
SPACELAB (PARTIAL P/L'S)					2	3	4	5	6	6	ETR/WTR	
APPLICATIONS (OA)												
WEATHER OBS & FORECASTING												
STORMSAT A/B						▽			▽		ETR	
TIROS N, N', O			▽			▽		▽	†		WTR	ATLAS F
NIMBUS G				▽							WTR	DELTA
ENVIRONMENTAL QUALITY												
ENVIRON MONITOR SAT A/B							▽		▽ †		WTR	
OCEAN COND MONITOR & FORECAST												
SEASAT A/B/C			▽				▽		†	▽	WTR	ATLAS F
EARTH RES DETECT & MONITOR												
TECH DEMONS SAT					▽							
LANDSAT C, D, D', E, E'		▽				▽	▽		▽ †	▽ †	WTR	DELTA
SEOS A										▽	ETR	
EARTH DYN MON & FORECAST												
EARTH SURVEY SAT								▽		†	WTR	
GRAVSAT A									▽		WTR	
LAGEOS	▽										WTR	DELTA
COMMUNICATIONS											ETR	
DISASTER WARNING							▽	▽			ETR	
SPACELAB *												
EARTH VIEWING APP LAB							▽	▽	▽▽	▽▽	ETR/WTR	
SPACE PROCESSING												
PALLETS (PARTIAL P/L'S)					2	3	3	3	6	9	ETR/WTR	
LABS (PARTIAL P/L'S)						1	1	1	2	3	ETR/WTR	
PARTIAL P/L'S					1	4	5	4	1	1	ETR/WTR	
APPLICATIONS (OTHER GOV)												
ITOS (NOAA)	▽	▽									WTR	DELTA
NOAA A/G			▽	▽	▽	▽	▽	▽	▽		WTR	ATLAS F
GOES (NOAA) A/G	▽	▽	▽		▽	▽		▽	▽		ETR	DELTA
EARTH RESOURCES							▽	▽	▽	▽	WTR	

▽ FY OF CONTRACT ▽ PROJECTED REQUIREMENT † RETRIEVAL * INCLUDES COMPLEMENTARY PAYLOADS

RESPONSIBLE OFFICE CODE O

PRELIMINARY

NON-NASA CIVIL PAYLOAD MODEL

8 MAR 1976

	FY 76	FY 77	FY 78	FY 79	FY 80	FY 81	FY 82	FY 83	FY 84	FY 85	LAUNCH SITE	VEHICLE CLASS
COMMUNICATIONS												
INTELSAT IVA	▽	▽▽	▽▽								ETR	ATLAS/CENT
INTELSAT V				▽	▽▽▽	▽▽▽					ETR	ATLAS/CENT
R & D PROTOTYPE										▽	ETR	ATLAS/CENT
COMSTAR	▽▽		▽								ETR	ATLAS/CENT
TDRSS				▽	▽▽▽▽						ETR	DELTA
COMSTAR F-O								▽▽▽			ETR	ATLAS/CENT
WESTAR		▽									ETR	DELTA
WESTAR F-O						▽▽	▽				ETR	DELTA
RCA	▽ ▽	▽									ETR	DELTA
RCA F-O								▽▽	▽		ETR	DELTA
MARISAT	▽▽▽										ETR	DELTA
OTHER U.S.				▽▽							ETR	DELTA
TELESAT			▽								ETR	DELTA
SIRIO		▽									ETR	DELTA
NATO III	▽▽			▽							ETR	DELTA
OTS		▽									ETR	DELTA
MAROTS			▽▽								ETR	DELTA
PALAPA	▽	▽									ETR	DELTA
CS			▽								ETR	DELTA
BSE			▽								ETR	DELTA
CTS	▽										ETR	DELTA
BRAZIL				▽▽▽							ETR	DELTA
OTHER FOREIGN						▽	▽	▽	▽	▽	ETR	DELTA
ARCOMSAT			▽	▽							ETR	DELTA
TRAFFIC MANAGEMENT												
AEROSAT					▽ ▽						ETR	DELTA
INMARSAT				▽▽							ETR	DELTA
INTERNAT'L AIR TRAFFIC							▽	▽▽	▽	▽	ETR	DELTA
FOREIGN SCIENTIFIC												
GEOS		▽									ETR	DELTA
EXOSAT				▽							ETR	DELTA
EURO SCIENTIFIC								▽			ETR	DELTA
METEOROLOGY												
GMS		▽									ETR	DELTA
METOSAT		▽									ETR	DELTA
INTERNAT'L MET SAT							▽▽				ETR	DELTA
ENVIRONMENTAL												
ALL WEATHER MICROWAVE									▽		WTR	DELTA
EARTH RESOURCES												
FOREIGN								▽		▽	WTR	DELTA
FOREIGN SPACELAB SORTIES												
DEDICATED P/L'S								▽	▽▽▽	▽▽▽	ETR	

▽ ELV ON CONTRACT ▽ PROJECTED REQUIREMENT

RESPONSIBLE OFFICE CODE MO

Third Draft
FJDOYLE:rb
September 9, 1976

VI-1

Dr. John Naugle
Associate Administrator
Code A, NASA Headquarters
Washington, D.C. 20546

Dear John:

The U.S. Geological Survey is aware that NASA is considering the development of a Large Format Camera (LFC) (305-mm focal length, 240x460-mm format) as a candidate sensor for the Space Shuttle, and wishes to endorse this development. We are also aware that Johnson Space Center has proposed carrying the Apollo 610-mm panoramic camera as a Shuttle pallet payload in conjunction with the LFC, and we would endorse this move if it does not jeopardize the LFC. We would appreciate the opportunity to review the technical specifications for these cameras during development.

The Survey has had an interest in this type of space photography extending back to recommendations made to us by the National Academy of Sciences in 1967. The configuration has also been supported by other bureaus within the Department of the Interior. In December 1970, USDI proposed the LFC to NASA for two unmanned, near-polar orbit film-recovery missions which were at that time called ERTS-C and -D, but the missions were never implemented.

We are aware that the Geosat Committee recommended the LFC be carried on Shuttle Orbital Flight Test 2 (OFT-2) in July 1979, and the Survey generally supports that recommendation. However we recognize the difficulty in having the camera available by that time, and would

far rather forego that flight opportunity entirely than see funds committed to some other frame camera configuration of lesser capability. We expect that whatever camera system is developed will become a near-standard pallet payload for subsequent Shuttle flights and would not like to see future photographic capability compromised simply to make OFT-2.

Despite our interest in the LFC and eventually a panoramic camera as a pallet payload, we are convinced that the only efficient mode of collecting space photography is from an unmanned, dedicated, reasonably long-life spacecraft in near-polar orbit. The Multi-Mission Modular Spacecraft (MMMS), to be launched and serviced by the Shuttle, holds forth that opportunity. We urge that the development of the LFC and pan camera assure that they will be compatible with that mode of operation, and suggest that the LFC might be a suitable payload for the Technology Demonstration Satellite on OFT-5. On-orbit servicing could include exchanging expended film magazines for fresh film, or replacement of the complete camera system.

It is difficult to justify space photography as an experiment, but we expect a real part of the Shuttle's role must be to provide operational capability to users of space data. Our Special Mapping Center has enough experience to assure that LFC photography (particularly if complemented by Apollo panoramic photography) would be technologically suitable for:

1. Compilation of new maps at 1:250,000 scale with 30-meter contour interval
2. Planimetric revision of 1:250,000-scale maps and topographic revision of large contour-interval maps in that series
3. Revision of 1:63,360-scale maps in Alaska
4. Original planimetric compilation and revision of our new series of 1:100,000-scale maps, and topographic compilation in areas of large contour interval
5. Developing a digital terrain data base with appreciably higher accuracy in many areas than that derived from the existing 1:250,000-scale contour maps
6. Establishing horizontal control in some areas for maps at scales as large as 1:25,000, and if panoramic photography is available, planimetric revision of this map series.

These are all important components of our National Mapping Program which could be expedited by use of LFC photography.

The Survey feels that the cost of developing camera systems is properly NASA's responsibility, but that operational costs would reasonably be assessed against the users. The Survey's mapping responsibilities are essentially confined to the United States and can for the most part be addressed by high-altitude aerial photography. We would expect to realize cost efficiency in compilation using space photography, but the overall cost effectiveness will depend eventually on the cost to us of obtaining photography

using the Shuttle capabilities. At the moment we have no realistic way of estimating what those costs will be, and we seek NASA's guidance in realistic planning.

We are confident that LFC and panoramic photography will be valuable to other mapping agencies and users of Earth resources data. We urge NASA to make these proposed capabilities known to these organizations.

Sincerely yours,

Director

Orbiter Photographic Acquisition System (OPAS)

(12-inch Mapping/24-inch Panoramic Camera System)

This system has been under evaluation at JSC for over two years as a means of deriving a camera technique which can satisfy the mineral explorationist, natural resource management, environmentalist, and cartographic communities' requirements and objectives during the Orbiter era. This evaluation has relied heavily on prior earth and lunar orbital programs and continued voicings from the operational user groups. Five major and overriding requirements continually present themselves for the parameters of a spaceborne photographic acquisition system. These are: geometric fidelity, spatial resolution, strong stereoscopic models, spectral content, and massive area coverage. These requirements dictate the following system componentry:

Mapping Camera - employing a large format for strong base-to-height ratios and a precision long focal length lens to provide a large scale and high spatial resolution for geometric control and cartographic base.

Panoramic Camera - large format and long focal length with very high spatial resolution for compilation detail and cartographic supplementation.

Multispectral Camera - a medium format, medium focal length 4-channel system with high spatial and spectral resolution to provide data on spectral content and detail.

The mapping camera and the panoramic cameras exist, but a suitable multispectral system does not. For early Orbiter applications (OFT-2 and subs) and to satisfy immediate and identifiable objectives, time and money economies can be capitalized on by going forward with a 12-inch large format mapping camera and a 24-inch panoramic camera as Orbiter's first integrated high performance photographic data acquisition system. Its initial cost can be amortized over the life of the Orbiter program through frequent mission applications, many of which could easily be cost reimbursible. Both systems exist and their design and hardware have been proven through application. Data from each of the cameras complement each other and produce an integrated data content package with a value manifold that of either camera used individually. The multispectral camera would be derived from previous NASA hardware designs (EREP S-190A and AIRP "AMPS") but could not be available for early Orbiter missions. However, it should be pursued through the study, evaluation, and preliminary design stages.

Orbiter 12-inch Mapping Camera (Large Format)

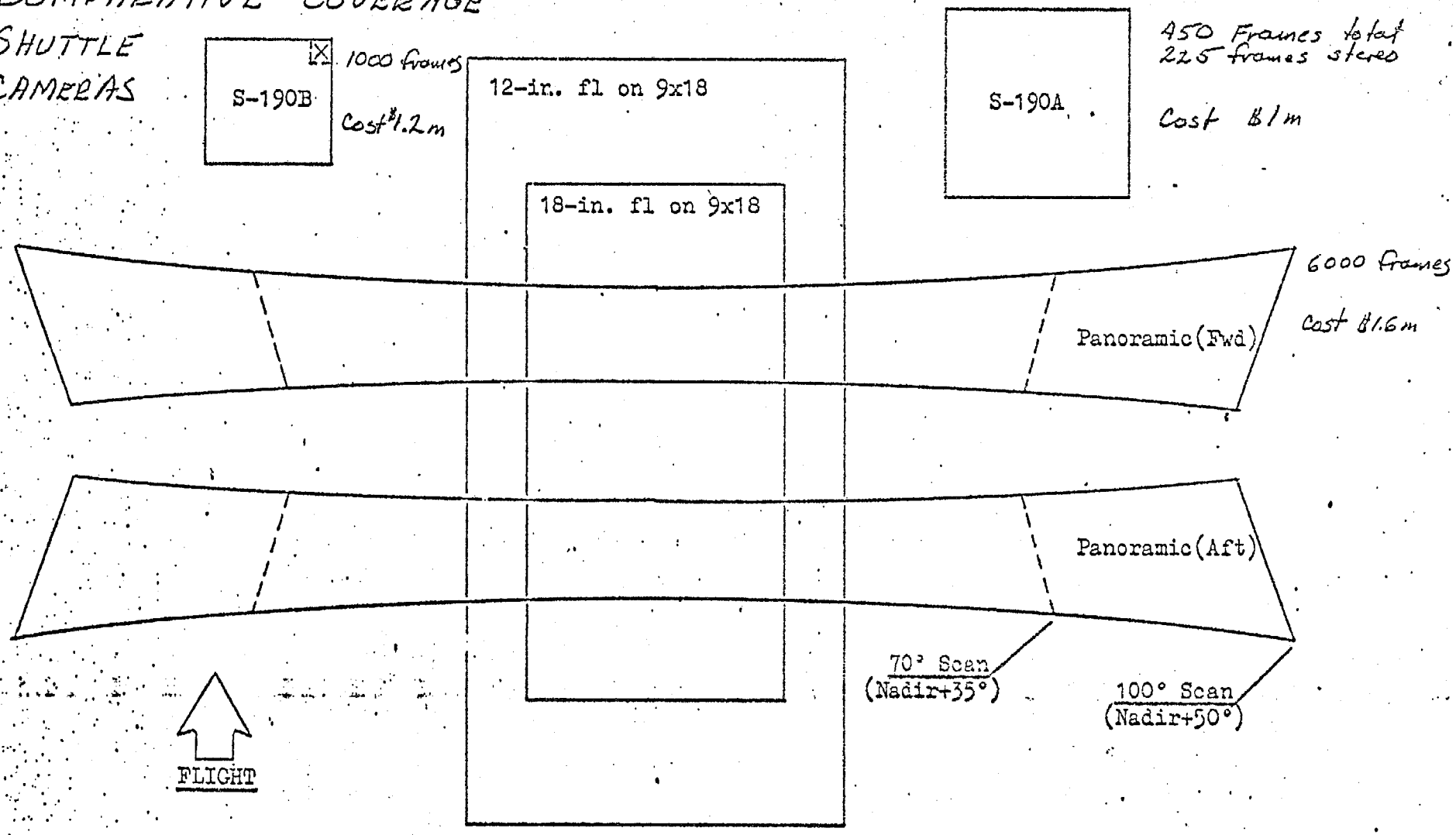
The mapping camera proposed for Orbiter OFT-2 is a large film format system (9- x 18-inch image area) with a 12-inch focal length aspheric cartographic lens developed for a classified program. The system produces extremely high spatial resolution and very good geometric fidelity. The combination of format size and focal length makes it possible to obtain very high base-to-height ratios in cascades of stereo pairs. This factor is most important in orbital photography where apparent flatness of the earth surface increases with altitude. As an example, sequencing the camera for 80 percent overlap of adjacent frames will produce stereo pairs with 80, 60, 40, and 20 percent overlap providing coverage of the entire groundtrack at base-to-height ratios of 0.3, 0.6, 0.9, and 1.2, respectively. This is of tremendous value to both geologic exploration and cartographic reduction. The ground footprint produced by this camera covers an area of 1.5 x altitude along the ground track by 0.75 x altitude across the track, and, at 120 nautical miles altitude, is capable of a low contrast ground resolution of approximately 15 meters.

The camera body (lens cone, lens, shutter, etc.) for this system has been designed, manufactured, tested, qualified, and flight tested and is, therefore, not a new development on the part of NASA. Only minor changes to this portion of the camera would be anticipated. The film magazine, however, will be a new development to avoid the volume, weight, complexity, and cost of the existing design. The costs of building the lens will be relatively low due to the availability of several million dollars worth of existing tooling and test plates. The new magazine will have a capacity of 2,000 feet of regular base film or approximately 1,200 exposures. At 120 nautical miles altitude and cycling for 80 percent overlap, this provides a continuous operating time of 2.96 hours which is equivalent to a contiguous ground track coverage of 80,000 kilometers (43,200 nautical miles). Compilation, viewing, and analysis equipment of the imagery produced by this camera is industry standard and readily available. This camera, used in conjunction with the 24-inch panoramic camera, will produce the most precision imagery acquisition system ever flown on aircraft or spacecraft and will suffice the requirements of the Orbiter era.

Orbiter 24-inch Panoramic Camera

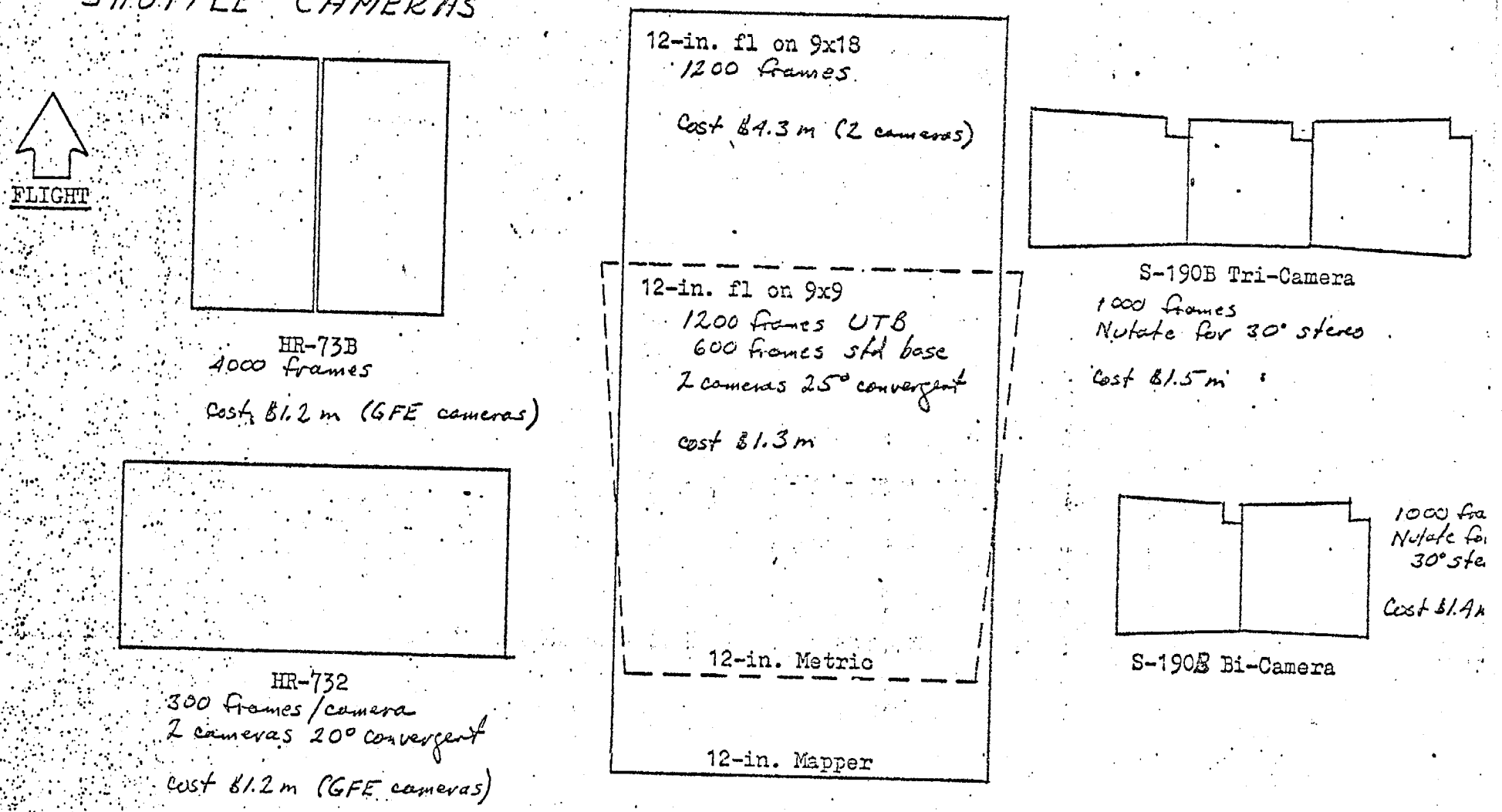
The panoramic camera proposed for Orbiter OFT-2 is a modified Apollo Panoramic Camera which was flown successfully on Apollos 15, 16, and 17, and which collected 4,700 precision high resolution photographs of the lunar surface. Two of these systems remain in the NASA inventory and are in storage at JSC, along with the ground support equipment. To render this camera suitable to Orbiter applications, certain mechanical and electrical design modifications will be required to adapt it to a 5 times increase in the forward velocity vector in earth orbit. Additionally, anticipated multi-flight applications will require strengthening of certain structural components. The camera can be operated in either monographic or convergent stereographic mode. In stereo mode, the base-to-height ratio is .443, which produces a very strong terrain relief. The ground footprint produced by this camera covers an area of 0.19 x altitude along the ground track by 2.3 x altitude across the track with a ground resolution (low contrast) at the nadir point of approximately 10 meters from an altitude of 120 nautical miles. The existing film capacity is 6,500 feet of thin base film which is equivalent to 1,700 exposures at a fixed scan of 100° or 2,800 exposures at a variable scan mode (50 to 70 degrees). At 120 nautical miles altitude in stereo mode and fixed scan, this is equivalent to a contiguous ground track coverage of 32,000 kilometers (17,250 nautical miles) or, in variable scan, more than 105,000 kilometers (56,700 nautical miles)--enough to cover the entire continental United States in one mission of 24 passes at 52 degrees inclination. This camera is suitable for geological exploration and cartographic supplementation. Federal agencies are currently using similar airborne systems for a wide range of census studies and map revisions. Compilation, viewing, and analysis equipment is readily available in the industry. This camera, used in conjunction with the 12-inch large format mapping camera, will produce the most precision imagery acquisition system ever flown on aircraft or spacecraft and will suffice the requirements of the Orbiter era.

COMPARATIVE COVERAGE SHUTTLE CAMERAS

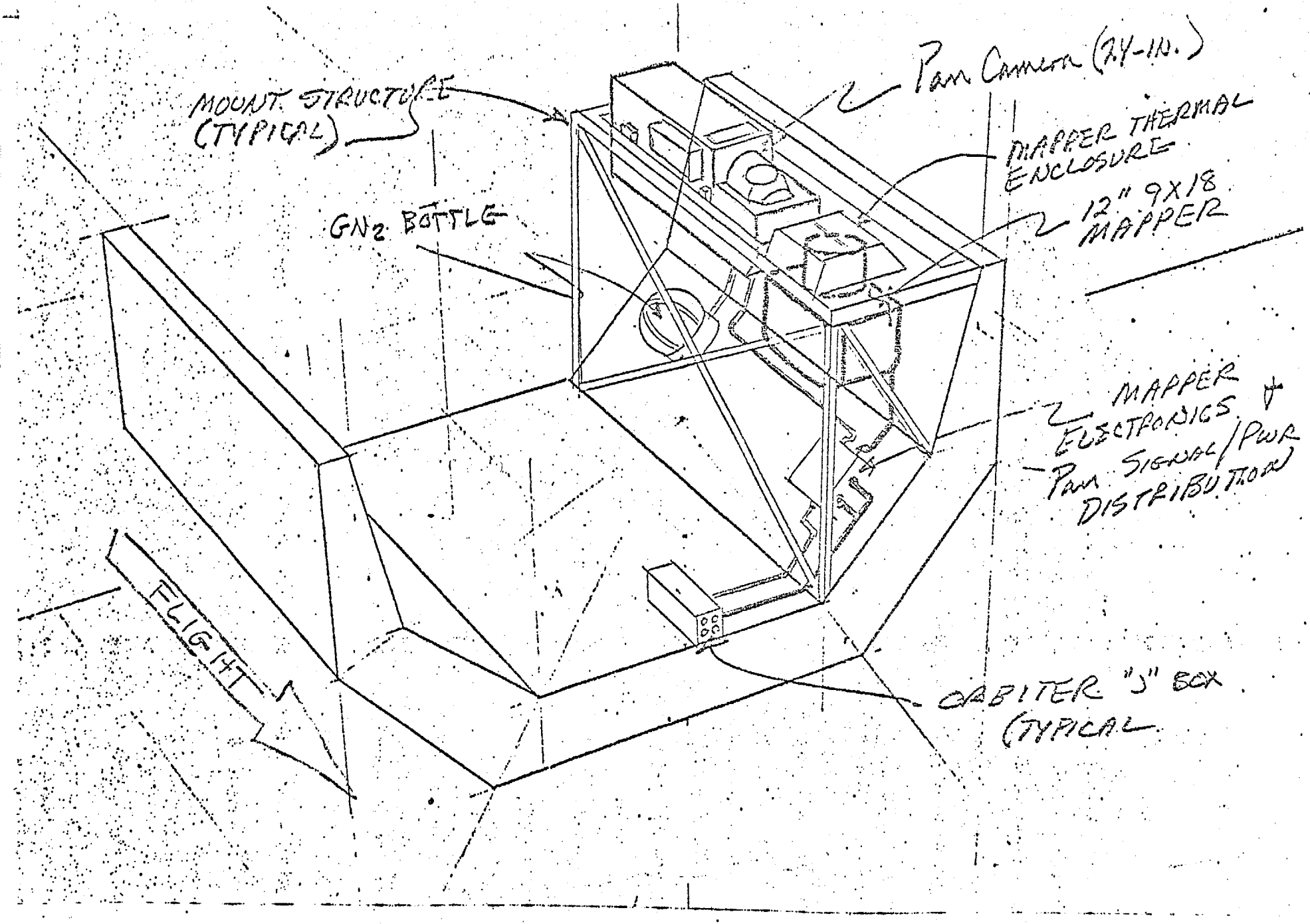


	Mapper	Mapper	S-190B	S-190A	Apollo Panoramic		
Focal Length	12-in.	18-in.	18-in.	6-in.	24-in. (4½x45-inch format)		
Format (inches)	9 x 18	9 x 18	4½x4½	2¼x2¼	Nadir	+35°	+50°
Footprint:							
Along Track	1.50 H	1.00 H	0.25 H	0.38 H	0.19 H	0.23 H	0.29 H
Across Track	0.75 H	0.5 H	0.25 H	0.38 H	-------	1.40 H	2.38 H
Area Covered at 120 nm (nm^2)	16,200	7,200	900	2,025	-------	4,200	8,200

COMPARATIVE COVERAGE SHUTTLE CAMERAS



	Mapper	Metric	HR-73B	HR-732	S-190B Bi-Cam	S-190B Tri-Cam
Focal Length	12-in.	12-in.	36-in.	24-in.	18-in.	18-in.
Format	9 x 18	9 x 9	9 x 18 (X2)	9 x 18	$4\frac{1}{2}$x$4\frac{1}{2}$ (X2)	$4\frac{1}{2}$x$4\frac{1}{2}$ (X3)
Footprint:						
Along Track	1.50 H	0.799H	0.50 H	0.375H	0.254H	0.257H
Across Track	0.75 H	0.847/ 0.708H	0.506H	0.75 H	0.49 H	0.743H
Area Covered at	16,200	8,950	3,600	4,050	1,800	2,750


MOUNT STRUCTURE (TYPICAL)
Pan Camera (24-IN.)
MAPPER THERMAL ENCLOSURE
12" 9X18 MAPPER
GN2 BOTTLE
MAPPER ELECTRONICS +
PAN SIGNAL/PWR DISTRIBUTION
FLIGHT
ORBITER "J" BOX (TYPICAL)

Mr. Clifford E. Charlesworth
Manager - Earth Resources Prog. Office
Code HA LBJ Space Center
NASA
Houston, Texas 77058

Dictated to Bill T.
VI-4

Dear Mr. Charlesworth:

Through various members of the GEOSAT (geology industries) Committee, I have learned that you and your staff are in the process of considering various earth resources payload options for the early (OFT) Shuttle Orbiter flights and particularly those which might constitute applications experiments suited to geologic studies.

As I'm sure you are aware, I was the recipient of a copy of a memorandum hand carried by Col. Wm. Pogue, of your office, to a GEOSAT Workshop in Flagstaff in May of this year. The memo, addressed to NASA Headquarters, discussed the OFT opportunity and listed possible photographic sensor candidates for discussion and consideration by the geology community represented at the Workshop. The Ad Hoc Committee subsequently communicated an overview of our space data needs to NASA/Headquarters and are presently in the process of publishing a report of our overall findings. The apparent urgency in defining the OFT opportunity led us to a selection and firm recommendation of a sensor candidate listed in the previously mentioned NASA memorandum. Our needs for OFT photographic data would best be met by a stereo, color, hi-resolution vertical frame type camera and our recommendation was documented as such.

I now understand that because of the OFT flight schedule combined with funding limitations and/or delays, our recommended system might not be feasible for the early flights. I fully understand and appreciate the problem.

My information regarding your present OFT payload deliberations indicates that an interim camera system might be under consideration; specifically, the NASA owned Apollo panoramic camera. My opinions on such a system for geologic surveys ~~is~~ are well documented particularly in the communications with various government offices when the same system was being considered for earth observations from ASTP. My opinion might best be illustrated as follows:

- the Apollo camera was selected for a geologic survey of the moon and it fulfilled its purpose.

- I included an identical camera in a concept for a privately funded geological survey satellite.

- I ~~supposed~~ say paid its application for a geologic survey from ASTP.

- It was selected as support for the primary "frame" camera at the GEOSAT Workshop.

Although the panoramic camera cannot fully replace our original GEOSAT recommendation for a strong stereo, "maplike" vertical photographic system for shuttle flights, it would make an attractive and useful interim system until it can be supplemented with the system which best meets our needs for expeditious geologic exploration and geologic mapping.

I am writing this letter not only as President of an energy resources exploration company but in this communication I am also representing the Executive Committee of GEOSAT whose goals for obtaining geologically suitable space data presently has the interest of 200 natural resource companies. On their and my behalf I want to thank you for your interest in our needs. If you need further clarification or elaboration of our requirements for photographic or other space sensor data, please feel free to call me.

Sincerely,

Pres. TGA &
Member Exec. Comm of GEOSAT

(4)

PHOTO-FILM CAMERA CANDIDATES FOR SHUTTLE-OFT (AS OF 8/11/76)

PRIMARY GEOSAT CAMERA REQUIREMENTS

	F.L. / FORMAT / ATTITUDE / MOUNT	MEET JULY 1979 SHUTTLE-OFT LAUNCH	10-METER GRD. (ALT. 260 KM)	"MAPLIKE" VERTICAL PERSP.	STEREO TO B/H. OF 0.9	COLOR/COLOR I.R. HI-RES FILMS	LARGEST SYNOPTIC "FOOTPRINT" SQ. KM.	GEOSAT RECOMMENDED
OFFERED BY NASA AT MAY '76 WORKSHOP	12 IN (9x18) VERT. FR.	✓	✓	✓	✓	✓	75000	✓
	18 IN (9x18) VERT. FR.		✓	✓		✓	33600	
	18 IN (9x18) CONV. FR. NOD MT.		✓		✓	✓	33600+	
	18 IN (9x18) CONV. FR. 2 CAM.		✓		✓	✓	33600+	
	30 IN (5 IN) PAN. CONV. NOD		✓			✓	35000	
	24 IN (5 IN) APOLLO PAN. NOD CONV.	✓	✓			✓	38000	SUPPORT ✓
CURRENTLY BEING CONSID. BY NASA (RE: FY'77 FUNDS)	6 IN (70mm) VERT. FR. 6-CAMERA	✓		✓		✓	9500	UNDERSTOOD NO LONGER BEING CONSIDERED (9/8/76 RJO.)
	18 IN (4.5x4.5) CONV. FR-2 CAM.	✓	✓		✓	✓	4160+	
	18 IN (4.5x4.5) CONV/VERT-3 CAM. NOD MT.	✓	✓		✓	✓	4160+	
	12 IN (9x9) CONV. FR-2 CAMERA	✓			✓	✓	38000	
	36 IN (9x18/18x18) NOD MT. CONV. FR.	✓		?	✓		9000+	
	24 IN (9x18) CONV. FR. 2 CAM.	✓			✓		18240+	

NASA DOCUMENT

VI-51

Orbiter 12-inch Mapping Camera (Large Format)

System Characteristics

Lens:	Focal Length	30.5 cm (12 inches)
	Aperture	f/6.0
	Type	Aspheric
	Spectral Range	450 to 900 nanometers
	Resolution (static)	
	Corners of format	50 l/mm (TOC= 2:1, 3414 film)
	Central 40° cone (avg)	95 l/mm " "
	AWAR	85 l/mm " "
	Distortion (radial)	± 20 micrometers
Image Format Size:		22.8 x 45.7 cm (9 x 18 inches)

Field of View:

	Radians	Degrees	Ratio to Altitude (H)
Along Track	1.287	73.74	1.50 x H
Across Tract	.7175	41.11	0.75 x H
Diagonal	1.3956	79.96	1.68 x H

Overlap (typical): (* Contiguous Track Coverage)

Frames	1 & 2	1 & 3	1 & 4	1 & 5	1 & 6
Percent	76*	52*	28*	04	
B/H Ratio	.36	.72	1.08	1.44	
Percent	80*	60*	40*	20*	
B/H Ratio	.30	.60	.90	1.20	
Percent	82*	64*	46*	28*	10
B/H Ratio	.27	.54	.81	1.08	1.35

Shutter:	Type	Rotary Disk, between lens
	Speeds	.010 to .002 seconds
Image Motion Compensation:		
	Type	Focal Frame Translation
	Range	.010 to .045 radians/second
Minimum Cycle Time:		6.5 seconds
Filters:	Anti-Vignetting	(in front of lens)
	Spectral	(within lens group)
Film:	Width	24.1 cm (9.5 inches)
	Length	610 meters (2,000 feet) regular base
	Exposures/roll	1,200 minimum
	Type: Standard	3414, 3400
	Optional	SO-131, SO-242, SO-127, SO-356
Fiducial Reference:		Format Edges (standard) Reseau Plate (optional)
Calibration:		AWAR (standard) Distortion (optional) Fiducials (optional)
Electrical Power:		
	115 V AC, 3Ø, 400 Hz	300 watts average 500 watts peak
	28 V DC	200 watts average 400 watts peak
Weight:	Camera	243 kg (536 lbs)
	Film	27 kg (60 lbs)
	Total	270 kg (696 lbs)

Jour. Research U.S. Geol. Survey
Vol. 4, No. 1, Jan.–Feb. 1976, p. 27–34

EXPLORATION FOR PORPHYRY COPPER DEPOSITS IN PAKISTAN USING DIGITAL PROCESSING OF LANDSAT–1 DATA

By ROBERT G. SCHMIDT, Reston, Va.

Abstract.—Rock-type classification by digital-computer processing of Landsat–1 (formerly ERTS–1) multispectral scanner data has been used to select 23 prospecting targets in the Chagai District, Pakistan, 5 of which have proved to be large areas of hydrothermally altered porphyry containing pyrite. The known porphyry copper deposit at Saindak was used as a control area. Empirical maximum and minimum apparent reflectance limits were selected for each multispectral scanner band in each rock type classified, and a relatively unrefined classification table was prepared. Where the values for all four bands fitred within the limits designated for a particular class, a symbol for the presumed rock type was printed by the computer at the appropriate location; these symbols formed a classification map. Drainage channels, areas of mineralized quartz diorite, areas of pyrite-rich rock, and the approximate limit of propylitic alteration were very well delineated on the computer-generated map of the test area. The classification method was then used to evaluate 2,100 km² in the Mashki Chah region, east of the test area, and a partial check of the results was made in the field. The results of the experiment show that outcrops of hydrothermally altered and mineralized rock can be identified from Landsat–1 data under favorable conditions. The empirical method of digital computer classification of the multispectral scanner data was relatively unrefined and rapid. The five mineralized prospecting sites identified are in locations that I would not have selected as favorable on the basis of geologic knowledge or photogeologic interpretation at the time of the investigation.

Mapping and mineral prospecting were undertaken at Saindak (fig. 1), in Pakistani Baluchistan, in 1962 because the locality was considered one of the more favorable areas in the Chagai District; the results of the study were reported by Ahmed, Khan, and Schmidt (1972). Detailed geologic and geophysical mapping and exploration at Saindak were later resumed by the Geological Survey of Pakistan (Khan, 1972; and Farah and Nazir Ullah, 1973), and the Resource Development Corporation of the Pakistan Government.

In 1962, after discovery of the disseminated copper sulfide ore body at Saindak, we noted that tonal changes and topographic expression related to hydrothermal alteration might be detected by optical remote sensing. When geological applications of data from the Earth Resources Technology Satellite, now Landsat, were still in a planning stage, the area of the Saindak deposit was discussed by U.S. Geological Survey personnel as an ideal test site for a remote-sensing experiment (fig. 2).

Two investigations concerned with direct detection of sulfide mineralization and hydrothermal alteration using Landsat–1 multispectral scanner data have used the porphyry copper deposit at Saindak as a test site because the deposit is large, has well-developed alteration zones and little vegetation, is well mapped, well exposed, and undisturbed. In addition, I was familiar with the deposit and region.

In the first investigation (Schmidt, 1974), false-color composite images made from Landsat–1 data were used to select light-toned areas that might be related to hydrothermal alteration. This rapid inexpensive method was handicapped by the general resemblance

FIGURE 1.—The Chagai District and Saindak, Pakistan.

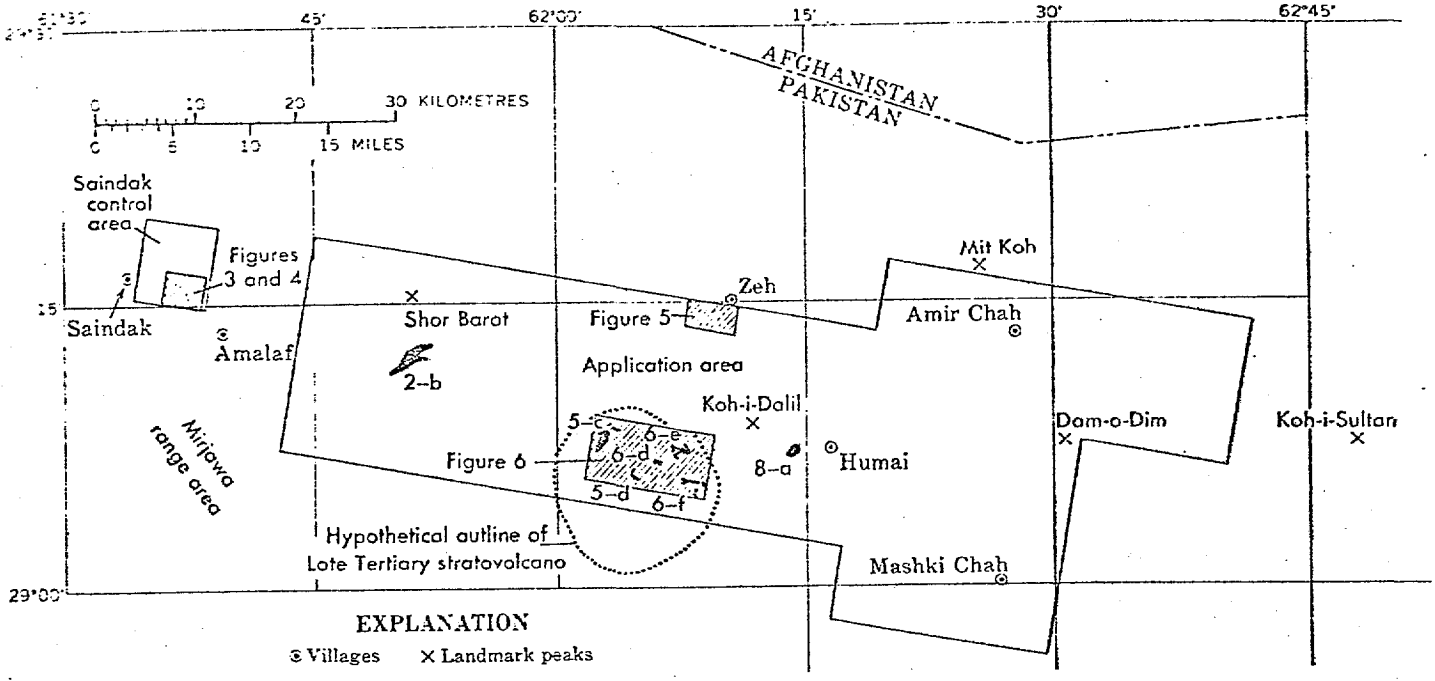


FIGURE 2.—The Saindak–Mashki Chah area of the western Chagai District showing the control area near Saindak and the area where the digital classification method was applied. The numbered locations near Koh-i-Dalil are mineralized prospect sites described in the text. Line pattern indicates areas detailed in other figures.

of hydrothermally altered areas to light-toned patches in dry washes and also to many areas mantled by eolian sand. Colors and densities for the four wave bands were selected to enhance the contrast between eolian sand and other light-toned features as much as possible. Many light-toned anomalies were eliminated as probable dry-wash material, and some others were rejected for other geologic reasons. The coincidence of anomalous light tones with areas shown as felsic intrusive rocks on published photogeologic maps (Hunting Survey Corp., Ltd., 1960) was considered favorable. Field checking showed that this initial assumption was probably false, as weathering and erosion of the hydrothermally altered porphyries of the region have resulted in topographic forms so low and rounded that they would probably not be classed as felsic intrusive rocks by photogeologic methods.

After the composite images were evaluated, even though several targets for field prospecting had been selected, it seemed desirable to seek a method that could discriminate more definitely between several surface materials that yielded similar tones.

In the second investigation, digital computer processing was used to classify data from the four multispectral scanner bands (MSS bands 4, 5, 6, and 7) and to attempt to identify the surficial material, particularly those types of material known to be related to hydrothermal alteration and mineralization, but also those light-toned surface types most likely to be confused with the hydrothermal alteration and mineralization-related surfaces.

In 1973, experimental work was undertaken by Ralph Bernstein and Bruce Clark of the Federal Systems Center, IBM Corp., on digital processing of Landsat–1 data as a method of locating mineral deposits. Clark extracted numeric data for the four MSS bands for each pixel from small test areas at Saindak chosen to represent single rock types and single rock-alteration types. Two experimental classification tables were then prepared, both of which delineated the Saindak mineralized area remarkably well (fig. 3), and which suggested that the method might be refined and used as an exploration tool. Computer services were purchased from the IBM Corp. by the U.S. Geological Survey to refine the classification tables for the area of the known deposit at Saindak, and then to use the refined method for the mineral evaluation of the 2,100 km² (810 mi²) of the Chagai District where the potential for finding porphyry copper deposits is good and where widely distributed eolian sand has made visual analysis of colored composites particularly troublesome (fig. 2). Mineral evaluation undertaken in this experiment resulted in the selection of 23 targets for field prospecting. After completion of the digital computer classification experiment, a field check was made, October 13–31, 1974, of some of the prospecting sites selected in the two studies.

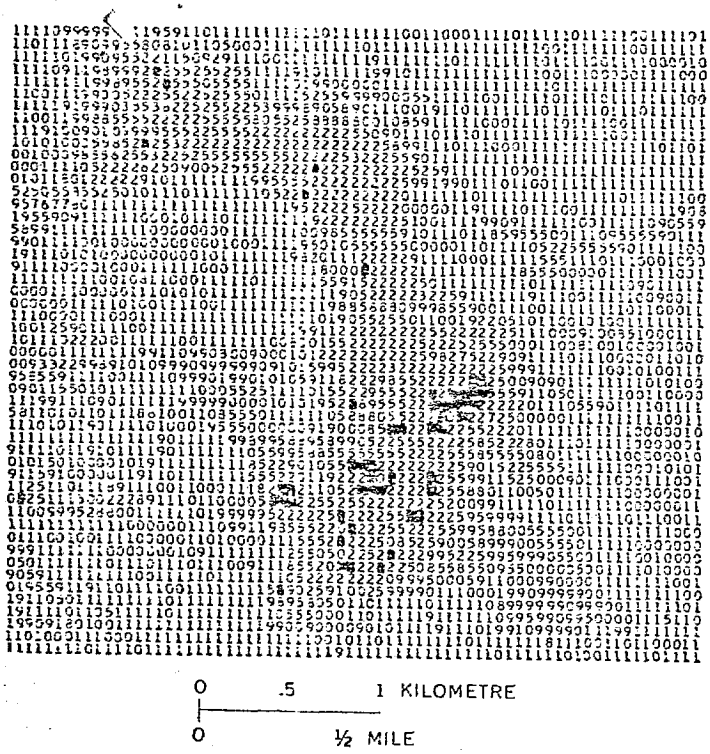


FIGURE 3.—Part of a 9-class map of Saindak control area. Class 4, one class used to identify mineralized quartz diorite, has been blackened to aid recognition and correlates closely with outcrops of mineralized quartz diorite (the class numbers are not the same as those in table 1). Classes 5, 8, and 9 together delineate dry wash areas. Class 2 outlines the area of known pyritic rock fairly well, but also appears in dry wash areas too frequently. Other classes do not fit known geology.

Acknowledgments.—The original color composite experiment was partly supported by the National Aeronautics and Space Administration. Financial support for the digital processing experiment and for part of the travel expenses of the field checking was provided by the EROS Office. Logistical support in the field in Pakistan was furnished by the Resource Development Corp., and the enthusiastic help given by their personnel made it possible to finish much more fieldwork in a short time than I had expected. Special thanks are due Dr. S. Durrani of Resource Development Corp. who accompanied me throughout the field checking.

REGIONAL GEOLOGY

The Mirjawa ranges, which include the Saindak deposit, and the Mashki Chah region where the classification method was applied, have somewhat different regional geology. The rocks of both areas are Cretaceous to Quaternary in age. The Mirjawa range area has mostly northwest-trending folded and much faulted sedimentary and volcanic-sedimentary strata containing small amounts of intrusive and extrusive igneous rock. The detailed geology of the Saindak area (Ahmed and others, 1972) is fairly representative of the geology of this border region. Cretaceous sedimentary rocks represent a wide variety of marine and continental depositional environments; lower Tertiary rocks are mostly shallow marine, and upper Tertiary-Quaternary strata are largely continental.

Saindak is a few kilometres east of the eastern edge of a wide area of regional metamorphism centered around a granitic intrusive body 40 km (25 mi) west of Saindak in Iran.

Rocks of the Mashki Chah region, a western extension of the Chagai Hills, are also folded and faulted, but the folding lacks the strong linear pattern characteristic of the Mirjawa ranges. Volcanic rocks with low dips, probably initial, are common and widespread. Intrusive rocks are more abundant; several volcanic necks are known, and volcanic cones and probably plug domes are present. Recently dried or still weakly flowing sinter-depositing saline springs, plus a few fumaroles on the volcano Koh-i-Sultan suggest that hydrothermal activity is continuing.

All the western part of Pakistan is covered by 1:253,440-scale photogeologic reconnaissance maps (Hunting Survey Corp., Ltd., 1960), but probably less than 1 percent of the Chagai District has been mapped in detail.

ECONOMIC GEOLOGY

Mineral reconnaissance in the Chagai District has been spotty and mostly in search of high-grade deposits; if a porphyry copper deposit had been noticed during early investigations, it might have been passed over as too low grade for consideration at that time. Several large areas of the Chagai District containing abundant intermediate and felsic volcanic rocks and small hypabyssal intrusive bodies of Cretaceous through Pleistocene age may be considered to have a good potential for large sulfide deposits of the porphyry copper type.

At Saindak, several small copper-bearing porphyritic quartz diorite stocks cut northward across the folded lower Tertiary stratigraphic section. The stocks may be cupolas on a single barely exposed granitic body 8 km (5 mi) long and as much as 1.5 km (1 mi) wide, or may be separate but related intrusive bodies. The group of stocks is surrounded by zones of contact metamorphism and hydrothermal alteration. The stocks are enclosed in a sulfide-rich envelope that contains as much as 15 percent pyrite by volume; the envelope in turn is surrounded by a zone of propylitic alteration in which pyroclastic rocks in particular are altered to a hard dark epidote-rich hornfels. The most highly

altered central part of the deposit is not fully defined, but there is pervasive quartz-sericitic alteration, and recent studies by Shahid Noor Khan are outlining a potassic alteration zone containing much hydrothermal biotite. Fluid inclusions are abundant in quartz grains. Many of the fluid inclusions contain halite crystals, and some gas-rich inclusions suggest formation of the quartz under near-boiling conditions (J. T. Nash, written commun., 1973).

The well-developed pattern of hydrothermal alteration zones and the general characteristics of the copper sulfide mineralization are similar to the simple ideal model of porphyry deposits described by Lowell and Guilbert (1970), but only detailed geological mapping plus extensive exploration drilling, such as the program now being carried out by the Government of Pakistan, can determine whether the deposit is of economic significance.

Hematite and iron sulfide skarns are common replacements of limestone beds in the propylitic zone of the deposit. Quartz-diorite dikes are common and locally abundant within the alteration zones and are easily identified on aerial photographs. Veins containing sparse argentiferous galena and copper minerals are also common within the propylitic zone. The occurrence together of skarns, dike swarms, and base-metal veins in other locations in the region is considered a favorable factor in prospecting for porphyry copper deposits.

The sulfide-rich zone, including both the intrusive porphyry stocks and the adjacent pyrite-rich country rock, has been eroded to form a light-toned valley. Desert soils associated with many porphyry copper deposits the world over have distinct red and orange color anomalies; this is true at part of the Saindak deposit as well, where the mineral natrojarosite has been identified in the pigmented material. In the central valley at Saindak, however, windblown and alluvial grains considerably dilute or cover much of the colored soil.

In plan view, this valley is encircled by a symmetrical rim of hills more rugged and darker in tone than the surrounding region (Ahmed and others, 1972, fig. 2). These hills, generally corresponding to the erosion-resistant zone of hornfels and propylitic alteration, form the outer boundary of the whole exploration target.

CLASSIFICATION EXPERIMENTS

Classification experiments were conducted in an area immediately surrounding the Saindak deposit. In Clark's experimentation, a shade print of MSS band 5 was prepared and used as a map to identify the location of individual data rectangles, or pixels, within areas of known rock type. Numeric data for the four MSS bands were extracted for each pixel in the known areas, the obviously unconforming pixels were rejected, and maximum and minimum apparent-reflectance limits were chosen for each rock type. The computer searched the data for the four bands for each pixel, and where the values fit the apparent-reflectance limits chosen for a class, the symbol for that class was printed at that location. When the observed values fit more than one class (where classes were set up with overlapping limiting values), a pixel was placed in the class that was considered earliest in the search sequence, resulting in some bias. Clark tested one table using nine classes (fig. 3) and one using five. Areas of mineralized quartz diorite were delineated very well, but the three classes of pyritic rock also included far too many pixels within light-toned dry-wash material. The drainage pattern was well defined.

In the EROS-funded experiment, three revisions were made and tested, and one alternate table was tried. In the early tables, there was no class for eolian sand because there were no areas of sand in the Saindak vicinity that we could use as control; the area where the method was to be applied, however, contained much sand and discrimination between mineralized felsic rock and eolian sand was expected to be a major problem. An area of known dune sand outside the known area was used to establish the sand classes.

The final classification table is shown as table 1. We have dealt with only three general types of materials: (1) mineralized rock, including intensely hydrothermally altered (quartz-sericite zone) quartz diorite, and pyritic rock, (2) alluvial and eolian materials, recently moved dry-wash alluvium and eolian sand being the materials most likely to be confused with the first group, and (3) a loose category of dark surfaces that includes both hornfels-type bedrock and many areas of desert-varnished lag-gravels (especially in class 10). The computer-generated classification map of the Saindak deposit that was made using the final classification table is shown in figure 4.

Four of the main surface types are each represented by two classes—a main, more restrictive class with reflectance limits in at least one band that make it exclusive from all other main classes, and a secondary class that overlaps the limits of at least one other class. Individual pixels classified in one of the main categories are intended to have a higher probability of correctly matching the surface material. Points classified in the secondary categories must be evaluated in the context of the classes of adjacent points. For example, if class 4 points (pyritic rock, secondary category)

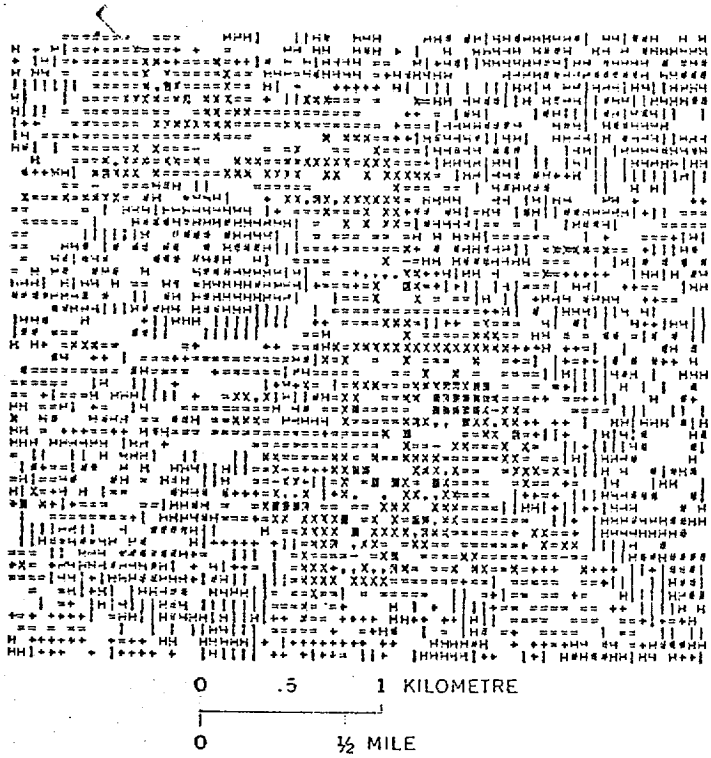


FIGURE 4.—Part of final classification map of test area.

TABLE 1.—*Final table used in digital classification of MSS data in the Chagai District, Pakistan*

Rock type	Class No.	Symbol	Band 4	Band 5	Band 6	Band 7
Mineralized quartz diorite.	1	■	46–50	52–60	59–60	18–22
	2	⊠	44–45	52–60	45–49	18–19
Pyritic rock	3	⊠	41–45	47–54	39–44	16–17
	4	X	41–45	47–54	39–44	16–19
Dry wash	5	=	39–46	39–46	35–44	14–17
	6	-	41–45	46–51	42–49	18–19
Boulder fan	7	+	33–40	39–46	30–35	9–16
Eolian sand	8	·	38–44	46–54	42–51	18–22
	9	·	45–45	46–127	42–127	18–63
Miscellaneous dark surfaces.	10	ı	33–36	28–38	29–35	11–15
	11	*	24–35	19–27	20–32	8–12
	12	H	29–36	28–38	20–28	9–14

occur interspersed with class 3 points (pyritic rock, primary category), the secondary class points probably represent the same material; however, if class 4 points are interspersed with points of one of the sand classes, the level of confidence in the classification drops, and the whole assemblage is regarded as sand.

In building the tables, as the acceptable reflectance limits of a class are narrowed, fewer matches are found. In classes 1 and 2, for example, if we choose limits that include most pixels in the training areas and also many pixels in all the areas of known mineralization, we also get false classifications in dry-wash material. The limits are subjectively adjusted wider or narrower so that enough points are classified correctly in the areas of known mineralization to call attention to those areas, and the false classifications are reduced to a minimum. The final tables used in this experiment have been revised a minimum number of times because revisions to the tables are costly and successive revisions generally achieve diminishing results. The use of few revisions, no ground checks during revisions, and the lack of incorporation of any ground-collected quantitative reflectance data into the experiment tend to place the whole study in the "quick and dirty" category.

APPLICATION OF METHOD TO EVALUATION OF 2,100 SQUARE KILOMETRES

The final classification table was used to evaluate an area in the Mashki Chah region adjacent to the Saindak test area, and considered to have good potential for porphyry copper deposits (fig. 2). The results were printed out in 13 computer-generated vertical strip maps. These maps were examined for groups of pixels classified as mineralized quartz diorite and pyritic rock, and about 50 groups or concentrations were identified. Each was then evaluated for probability of correct classification, relationship to concentrations of other classes, and comparison with known geologic data—both rock types and occurrences of hydrothermal mineralization. From this examination, localities most deserving reconnaissance checking in the field were chosen, and these prospecting targets were graded into priority categories. The grading process was of necessity very arbitrary. Thirty target areas were selected, four of first priority and the rest of lesser interest. The locations of these targets were transferred visually to an enlarged digitally enhanced image of MSS band 5 in order to simplify location in the field.

As part of the field check, all anomalous areas were first examined on stereoscopic pairs of 1:40,000-scale aerial photographs. At this point it was possible to reject seven areas as related to windblown sand (fig. 5), leaving 23 sites. Nineteen sites were examined in the field, and four desirable sites were bypassed in the field checks. Of the four "high-priority" prospecting sites, none were found to be significantly mineralized or hydrothermally altered, except for a little alteration in part of area 2-b (fig. 2). Of the five sites found to be outcrops of hydrothermally altered sulfide-rich rock, two had been rated as "medium priority" prospects, and three as "low priority." Two additional sites have altered rock containing some sulfide but seem less attractive for prospecting at this time.

Two areas recommended in the false-color composite study were also examined in the classification experiment, but neither was classed as mineralized by the digital-processing method.

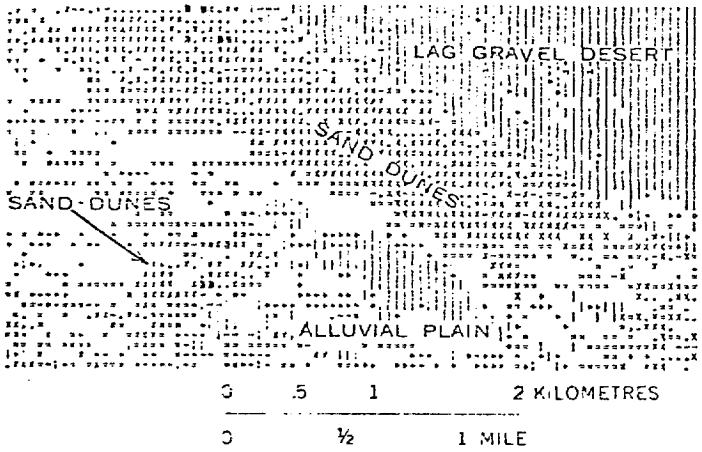


FIGURE 5.—Area of dunes near Zeh (see fig. 2) falsely classified as mineralized quartz diorite (classes 1 and 2) and pyritic rock (classes 3 and 4).

THE NEWLY IDENTIFIED AREAS OF MINERALIZATION

The areas of mineralization found in this investigation are in two general locations. At the first location, four of the mineralized sites (5–c, 5–d, 6–d, 6–e) occur in what is probably the central core of the eroded remnant of a large stratovolcano (figs. 2 and 6). Of the four, site 5–c seems to be a separate mineralized area, but sites 5–d, 6–d, and 6–e may be parts of a single large mineralized body as the areas between the sites are covered by Holocene alluvium. The second location (site 8–a, fig. 2) is 15 km (9 mi) east of site 6–e and well outside the core of the stratovolcano, although it may be within the flank of the old volcano edifice.

Site 5–c (estimated area mineralized, 2.3 km²).—The large area of site 5–c seems underlain by light-toned rock with silicic, argillic, and probably some sericitic alteration. Some of this rock is porphyry and probably tuff and sandstone or tuffaceous sandstone. Most sulfide was present formerly as veinlets forming stockworks, and disseminated sulfide was probably minor. No copper minerals were noted in the field.

Site 5–d (estimated area mineralized, 0.5 km²).—The northern part of site 5–d consists of scattered small exposures surrounded by dry-wash alluvium. The outcrops are quartz-sericite altered porphyry having resistant ribs of silicic rock and vein quartz. The rock contains limonite stains and sulfide casts, but not as abundantly as at sites 6–d and 6–e.

The southern part of site 5–d consists of siliceous and argillic altered porphyry and tuffaceous rock. Pseudomorphs after sulfide are less abundant than in other sites described; some sulfide seems to have been disseminated and some was in veinlets. Where un-

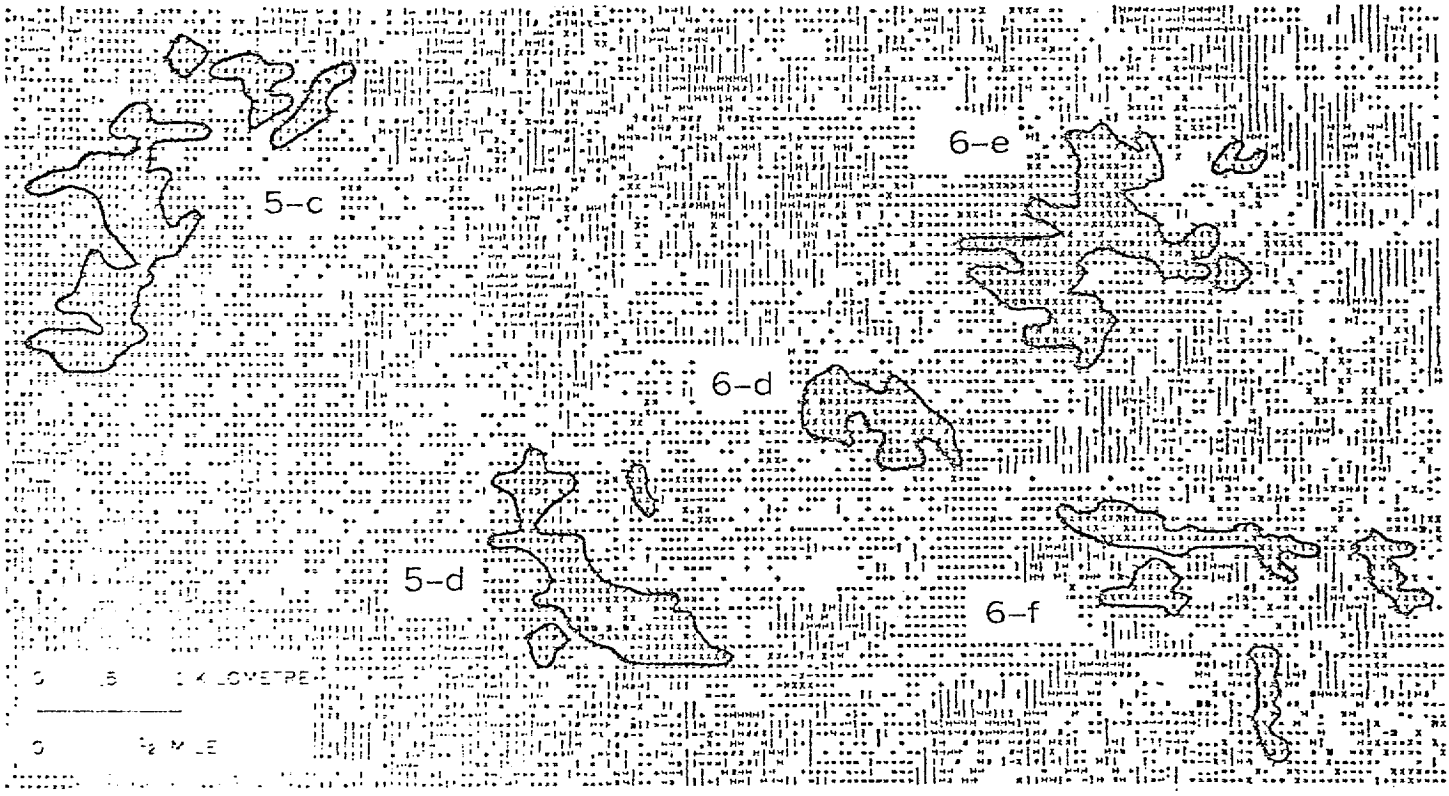


FIGURE 6.—Classification map of an area west of Koh-i-Dalil showing five areas classed as "mineralized."

leached sulfide was seen, it appears to be only pyrite. Black tourmaline is common locally.

The outcrops in site 5–d tend to be mantled by hard siliceous material that may represent only narrow altered zones and may not be truly representative of the main mass of rock.

Site 6–d (estimated area mineralized, 0.8 km²).—The bedrock at site 6–d is all felsic porphyry having intense quartz-sericite and argillic alteration. The pyrite mineralization, part disseminated and part in veinlets, is pervasive and is estimated at 5–10 percent of the rock volume. The sulfide is now mostly leached, but residual masses of unleached rock are not as rare here as at the other sites. Several places have traces of oxidized copper minerals in rocks or soils; at one place, weathered pyrite has rather common copper carbonate stains, and the analysis was 0.3 percent copper. Jarositic and gypsum-rich soils are common. This is the most intensively altered area found in the field investigation.

Site 6–e (estimated area mineralized, 0.3 km²).—Site 6–e is an area of highly altered quartz-rich porphyry. In the northwest end are many residual blocks containing 5–10 percent pyrite, but only minor traces of copper minerals. In a brief stop at the southeast end of the area, we saw what may be argillic alteration in rock from which all sulfides have been leached.

Site 8–a (estimated area mineralized, 0.8 km²).—Site 8–a, an area of extensive sulfide mineralization associated with what is probably intrusive feldspar porphyry and well-formed propylitic and quartz-sericitic(?) alteration zones, has many of the characteristics of a porphyry copper deposit. The site forms a low topographic basin bounded by major dry washes on the east and west, by an andesite flow-capped mesa on the north, and a low range of dark andesitic(?) hills on the south. The area is partly rimmed on the east side by hills of propylitically altered gray feldspar quartz porphyry. Westward, this grades into a zone containing local pockets and lenses of argillic alteration, then into the most highly altered central core. Hydrothermal alteration of the central part of the deposit is intense, resulting in a very quartz-rich rock containing abundant (5–10 volume percent) pyrite and perhaps other sulfides. Most of the sulfides have been completely leached out, leaving voids and limonite-filled cavities; only a few cores of unleached rock remain. Jarositic soils and gypsum are common throughout the valley. We saw only a few traces of copper minerals.

The intrusive porphyry is enclosed in shale and fine sandstone; in the northern part of the valley, the intense alteration extends to the edge of the porphyry and beyond to include a sizable area of sandstone as well. Abundance of limonite suggests that the altered sandstone was as pyritic as the altered porphyry.

A massive rock near the center of the valley is perhaps a fine uniform-textured phase of the porphyry, a separate intrusive body, or a well-indurated tuff. It is thoroughly altered (the alteration tentatively classified as argillic) and locally contains traces of copper.

A white porphyry found at several places in the mineralized zone may be an altered form of the main porphyry or perhaps a separate intrusive body which may have been the activating agent in the mineralization.

Leaching of the outcrops at all of the sites has been intense; if any copper was formerly present, the possibility of a secondary enriched zone seems very good. The leaching is so intense that the lack of visible copper minerals is not too negative a factor. The lack of sparsely mineralized quartz veins in the propylitic zone at site 8–a is not consistent with many other porphyries, however.

Two of the sites examined have lesser amounts of hydrothermal alteration and sulfide. The east end of area 2–b (fig. 2) is underlain by a very light-toned quartz feldspar porphyry. I believe that some quartz and argillic alteration has taken place, but the rock may be originally silicic and relatively fresh. Iron oxide staining is abundant in a few restricted places. Neither sulfides nor copper carbonate stains were noted in the field. The middle and western parts of area 2–b are propylitically altered sedimentary and volcanic rocks that have probably very little economic mineral potential. Site 6–f (figs. 2 and 6), has been examined only near the east end where some hydrothermal rock alteration and probably pyrite mineralization is present, but most of the tonal anomaly is due to dune sand. The western part of the site has not been inspected.

The mineralized areas, 5–c, 5–d, 6–d, 6–e, and 8–a, which I believe to be of the porphyry type, may be important deposits. If the sulfide near the surface contains no copper, we are possibly seeing only the top of a porphyry and the copper zone may be deeper. If even a little copper has been present in the now leached sulfide, the chance for a supergene ore body is excellent.

SUMMARY

A method of simple digital classification that uses areas of known hydrothermal alteration and mineralized and altered intrusive stock as control areas has been developed. The classification table was then used to evaluate 2,100 km² of area regarded as having a high potential for deposits of the porphyry copper type. Office evaluation of the resulting survey yielded 23 prospecting targets, 4 of which were considered high-

priority. Field checks of 19 sites revealed that five sites were sizable areas of hydrothermally altered rock containing abundant sulfide, which is disseminated or in stockwork veins. Although the classification method used was relatively simple and unrefined, the number of sulfide-bearing areas identified was outstanding, and the falsely classified areas were not so many as to require an unreasonable amount of field checking.

The sulfide-bearing rocks are mostly porphyritic, and although copper minerals have been seen in only a few places, all the pyritic rocks are potentially the pyrite zones of porphyry-copper-type deposits. Thorough leaching of the surface rocks has removed whatever copper may have been present. Secondary copper enriched zones may exist at depth.

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ASA-S-76-11643

Goetz – "Future Planning"

PLANNED NASA MISSIONS APPLICABLE TO GEOLOGIC APPLICATIONS

PLANNED	LAUNCH DATE
LANDSAT C	SEPT 1977
HEAT CAPACITY MAPPING MISSION (HCMM)	APR 1978
SEASAT	MAY 1978
SHUTTLE ORBITAL FLIGHT TEST (OFT) 2	JULY 1979
MAGSAT	AUG 1980
STEREOSAT	(?)
LANDSAT D	1981

NASA-S-76-11644

CANDIDATE MISSIONS PROPOSED BY GEOLOGIC COMMUNITY

- ROCKSAT
- SARASAT
- THIRSSAT
- GIMSAT

NASA-S-76-11645

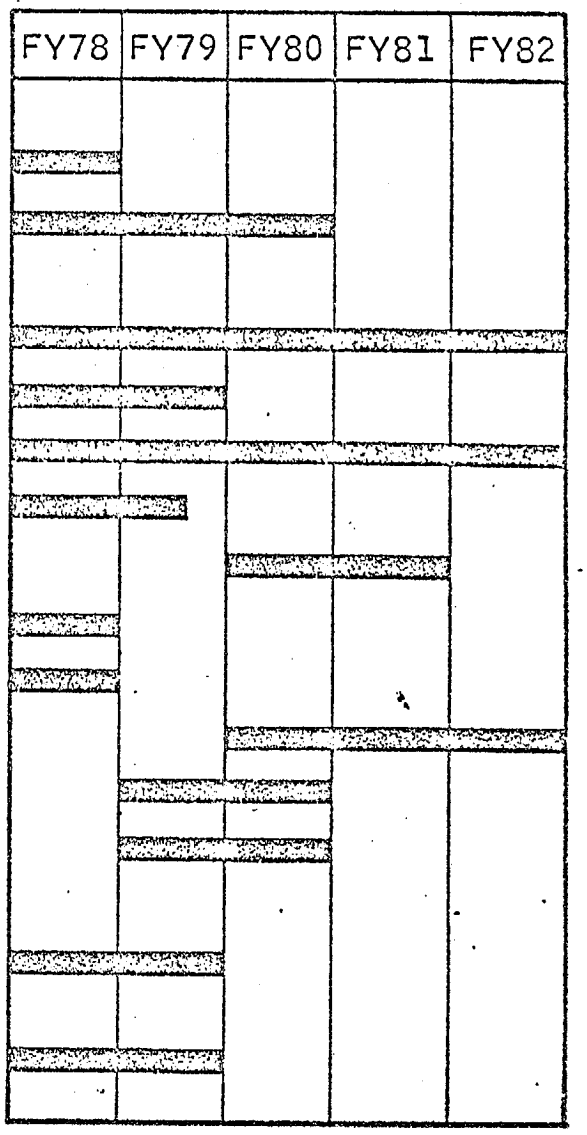
MINERAL AND ENERGY RESOURCES
PRELIMINARY 5-YEAR RESEARCH PLAN - NASA
TASK LISTING AND SCHEDULE

Potential Verification
Feasibility of Success
Overall Priority

TASKS

- MODEL DEVELOPMENT
  - EXPLORATION MODEL DEVELOPMENT
  - RELATING OBSERVABLES TO COPPER PORPHYRY DEPOSIT
- IMPROVED LITHOLOGY AND ALTERATION DISCRIMINATION
  - MULTISOURCE DATA TECHNIQUES
  - MSS BAND OPTIMINATION (0.5 - 14 μm)
  - X&L BAND IMAGING RADAR EVALUATION
  - THERMAL INERTIA TECHNIQUES
  - RESTRAHLEN BAND TECHNIQUES
  - PASSIVE MICROWAVE TECHNIQUES
  - SIMULATED SEASAT RADAR EVALUATION
  - TEXTURAL AND SPATIAL CLASSIFICATION TECHNIQUES
  - INDUCED FLUORESCENCE TECHNIQUES
  - ACTIVE/PASSIVE SCANNER EVALUATION
- IMPROVED STRUCTURAL FEATURE RECOGNITION
  - DIFFERENTIATING GEOLOGICALLY IMPORTANT FEATURES FROM OTHER FEATURES
  - IMPROVING STRUCTURAL FEATURE EXTRACTION TECHNIQUES

SCHEDULE



NASA-S-76-11646

MINERAL AND ENERGY RESOURCES
PRELIMINARY 5-YEAR RESEARCH PLAN - NASA

TASK LISTING AND SCHEDULE (CONT)

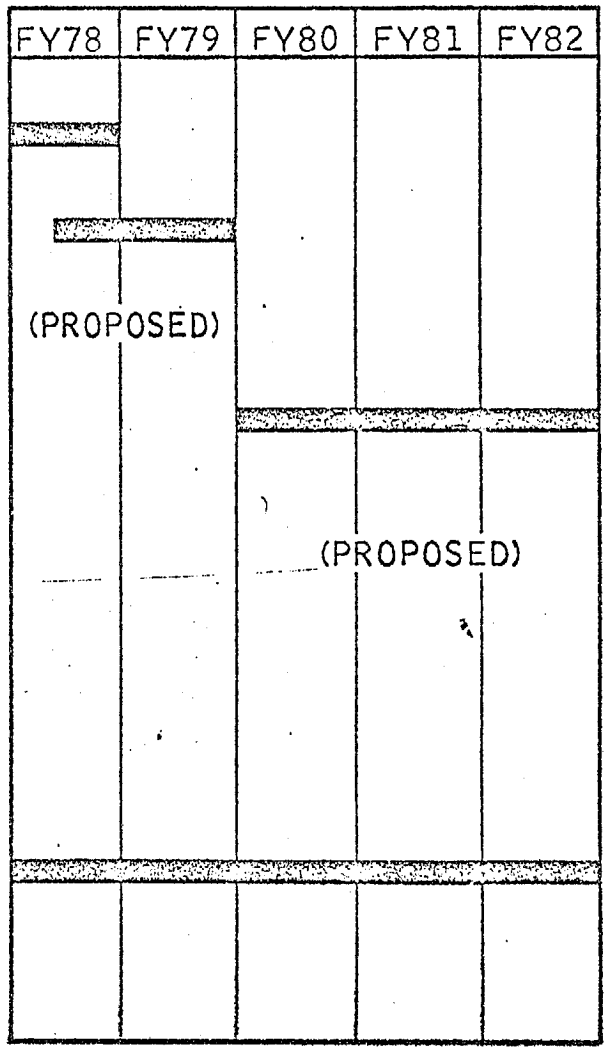
TASKS

- VEGETATIVE ANOMALY IDENTIFICATION
  - STATISTICAL ANALYSIS OF KNOWN VEGETATIVE ANOMALIES WITH LANDSAT DATA
  - VEGETATIVE ANOMALY DISCRIMINATION WITH THEMATIC MAPPER SIMULATOR
  - TRACE METAL EFFECT ON VEGETATION SPECTRAL RESPONSE
  - FRAUNHOFFER LINE DETECTION AND ACTIVE FLUORESCENCE STIMULATION OF VEGETATIVE ANOMALIES
- DETECTION OF GEOTHERMAL SOURCES
  - DETECTION OF GEOTHERMAL SOURCES WITH THERMAL IR DATA
- ENGINEERING GEOLOGY APPLICATIONS

  (NO RESEARCH TASKS DEFINED)
- DEFINITION OF SPECIALIZED GEOLOGIC SATELLITES
  - (CONDUCTED UNDER "SENSORS" - WILL INCLUDE STUDIES SUCH AS:

    - STEREOSAT SYSTEMS DEFINITION
    - OFT 2 CAMERA REQUIREMENTS

SCHEDULE



NASA-S-76-11647

MINERAL & ENERGY RESOURCES
PRELIMINARY 5-YEAR RESEARCH PLAN-NASA
TASK DESCRIPTIONS

MODEL DEVELOPMENT

- EXPLORATION MODEL DEVELOPMENT
  - ESTABLISH COMPREHENSIVE EXPLORATION MODELS FOR IMPORTANT MINERAL COMMODITIES RELATING TYPES OF SURFACE OBSERVABLES TO TYPES OF DEPOSITS
  - STATISTICALLY EVALUATE MODELS BY COMPARING CORRELATION OF OBSERVABLES TO OCCURRENCE OF KNOWN DEPOSITS
  - USE DATA FROM LITERATURE, GEOSAT COMMITTEE, OTHER SOURCES
- RELATING OBSERVABLES TO COPPER PORPHYRY DEPOSIT
  - TEST REMOTE SENSING TECHNIQUES FOR DISCRIMINATING EVIDENCE OF COPPER PORPHYRY DEPOSIT
  - USE AIRCRAFT MSS, FIELD SPECTROSCOPY, AND LANDSAT DATA
  - COOPERATE WITH GEOSAT TO ACQUIRE GEOPHYSICAL AND FIELD DATA

NASA-S-76-11648

IMPROVED LITHOLOGY & ALTERATION DISCRIMINATION

MINERAL & ENERGY RESOURCES PRELIMINARY 5-YEAR RESEARCH PLAN-NASA

TASK DESCRIPTION

- MULTISOURCE DATA TECHNIQUES
  - USE STATISTICAL METHODS AND DIGITAL IMAGE PROCESSING COMBINED WITH MULTISOURCE DATA (MULTISPECTRAL VIS, IR, AND THERMAL; MULTIFREQUENCY, MULTIPOLARIZATION MICROWAVE) TO OPTIMIZE SEPARABILITY OF LITHOLOGIC UNITS

MULTISPECTRAL SCANNER (MSS) OPTIMIZATION (0.4 - 14 μm)

- COMPLETE CONSTRUCTION AND TESTING OF PORTABLE EMISSION SPECTROMETER COVERING 3 - 4 μm) REGION AND OBTAIN SPECTRA OF A SUITE OF ROCK TYPES
- STATISTICALLY ANALYZE DATA WITH SPECTRA FROM PORTABLE FIELD REFLECTANCE SPECTROMETER (0.5 - 2.5 μm) TO DETERMINE OPTIMUM BANDS FOR DISCRIMINATING ALTERED ROCKS

MINERAL AND ENERGY RESOURCES
PRELIMINARY 5-YEAR RESEARCH PLAN - NASA
TASK DESCRIPTIONS

IMPROVED LITHOLOGY AND ALTERATION DISCRIMINATION (CONT)

- PASSIVE MICROWAVE TECHNIQUES
  - DETERMINE THE RELATIONSHIP OF MICROWAVE EMISSITY VARIATIONS TO TYPES OF GEOLOGIC MATERIALS AND EVALUATE POTENTIAL FOR SEPARATING LITHOLOGIES
- SIMULATED SEASAT RADAR EVALUATION
  - SIMULATE SEASAT IMAGING RADAR DATA BY ACQUIRING AND DEGRADING LOW INCIDENCE ANGLE L-BAND AIRCRAFT IMAGERY
  - EVALUATE USEFULNESS IN RECOGNIZING LIGHOLOGIC UNITS
- TEXTURAL AND SPATIAL CLASSIFICATION TECHNIQUES
  - DEVELOP AND TEST CLASSIFICATION ALGORITHMS FOR DIFFERENTIATING LITHOLOGIES BASED ON TEXTURAL CHARACTERISTICS. INITIAL EFFORT SHOULD BE IN VIS, IR REGION. LATER WORK SHOULD INCORPORATE MICROWAVE REGION

NASA-S-76-11650

MINERAL AND ENERGY RESOURCES
PRELIMINARY 5-YEAR RESEARCH PLAN - NASA
TASK DESCRIPTIONS

IMPROVED LITHOLOGY AND ALTERATION DISCRIMINATION (CONT)

- X&L BAND IMAGING RADAR EVALUATION
  - OBTAIN X&L BAND, DUAL POLORIZED, CALIBRATED, SYNTHETIC APERTURE DATA OVER GEOLOGICALLY WELL KNOWN SITES
  - EVALUATE EFFECTS OF TOPOGRAPHY AND SURFACE TEXTURE ON RETAINED SIGNAL
  - DETERMINE AND COMPARE ABILITY TO DISCRIMINATE LITHOLOGIES
- THERMAL INERTIA TECHNIQUES
  - OBTAIN LABORATORY AND FIELD DATA ON THERMAL INERTIAS OF ROCKS AND SOILS AND THE EFFECT OF SOIL MOISTURE ON THERMAL INERTIAS
  - DETERMINE CAPABILITY TO DISCRIMINATE MAJOR LITHOLOGIES BY COMPARING DATA FROM THERMAL INERTIA COMPUTER MODEL WITH ACTUAL DATA
- RESTRAHLEN BAND TECHNIQUES
  - DETERMINE INCREASED EFFECTIVENESS OF DISCRIMINATING LITHOLOGIC UNITS BY USING TWO THERMAL CHANNELS TO RECOGNIZE RESTRAHLEN BAND EMITTANCE CHARACTERISTICS

NASA-S-76-11651

MINERAL AND ENERGY RESOURCES
PRELIMINARY 5-YEAR RESEARCH PLAN-NASA
TASK DESCRIPTIONS

IMPROVED LITHOLOGY AND ALTERATION DISCRIMINATION (CONT)

- INDUCED FLUORESCENCE TECHNIQUES
  - DEVELOP AND TEST TECHNIQUES TO DISCRIMINATE LITHOLOGIES BASED ON INDUCED FLUORESCENSE DIFFERENCES IN ROCKS
- ACTIVE/PASSIVE SCANNER EVALUATION
  - DETERMINE IMPROVEMENTS IN LITHOLOGIC DISCRIMINATION POSSIBLE WITH DATA FROM ACTIVE/PASSIVE SCANNER UNDER DEVELOPMENT
  - SCANNER PROVIDES POTENTIAL OF IMAGINING IN NARROW ABSORPTION BANDS OF MINERALS; COMPARISONS OF SIGNALS FROM THESE BANDS WITH SIGNALS JUST OUTSIDE BANDS CAN REVEAL PRESENCE OF CERTAIN MINERALS, THEREBY IMPROVING DISCRIMINATION AND CLASSIFICATION

NASA-S-76-11652

MINERAL AND ENERGY RESOURCES
PRELIMINARY 5-YEAR RESEARCH PLAN-NASA
TASK DESCRIPTIONS

IMPROVED STRUCTURAL FEATURE RECONGNITION

- DIFFERENTIATING GEOLOGICALLY IMPORTANT FEATURES FROM OTHER FEATURES
  - QUANTIFY BASIS FOR DISTINGUISHING MEANINGFUL FEATURES FROM OTHER FEATURES BASED ON MODELS
- IMPROVING STRUCTURAL FEATURE EXTRACTION TECHNIQUES
  - DEVELOP AND TEST OPTICAL AND COMPUTERIZED TECHNIQUES SUCH AS HALOGRAPHY AND DIGITAL FILTERING TO IMPROVE RECOGNITION AND SEPARATE GEOLOGICAL MEANINGFUL FEATURES FROM OTHER FEATURES

ASA-S-76-11653

MINERAL AND ENERGY RESOURCES

PRELIMINARY 5-YEAR RESEARCH PLAN - NASA

TASK DESCRIPTIONS

VEGETATIVE ANOMALY IDENTIFICATION

- STATISTICAL ANALYSIS OF KNOWN VEGETATIVE ANOMALIES WITH LANDSAT DATA
  - STATISTICALLY COMPARE DISTINGUISHABILITY OF KNOWN AREAS OF STRESSED VEGETATION RELATED TO KNOWN MINERALIZATION USING DIGITALLY PROCESSED LANDSAT DATA
- VEGETATIVE ANOMALY DISCRIMINATION WITH THEMATIC MAPPER SIMULATOR
  - EVALUATE IMPROVEMENT EXPECTED IN DISCRIMINATING VEGETATIVE ANOMALIES WITH LANDSAT D BY STATISTICALLY EXAMINING KNOWN ANOMALIES WITH AIRCRAFT-BORNE THEMATIC MAPPER SIMULATOR AND COMPARING TO RESULTS FROM ABOVE STUDY
- TRACE METAL EFFECT ON VEGETATION SPECTRAL RESPONSE
  - ESTABLISH EXPERIMENTAL PLOTS OF PLANTS IN SOILS OF KNOWN CONCENTRATIONS OF TRACE METALS
  - DETERMINE EFFECT OF METALS ON PLANT REFLECTANCE/EMITTANCE
  - COMPARE RESULTS TO KNOWN BIOGEOCHEMICAL ANOMALIES
- FRAUNHOFFER LINE DETECTION AND ACTIVE FLUORESCENCE STIMULATION OF VEGETATIVE ANOMALIES
  - DETERMINE THE USEFULNESS OF THESE TECHNIQUES IN IDENTIFYING VEGETATIVE ANOMALIES RELATED TO HIGH METAL CONCENTRATIONS

NASA-S-76-11654

MINERAL AND ENERGY RESOURCES

PRELIMINARY 5-YEAR RESEARCH PLAN - NASA

TASK DESCRIPTIONS

DETECTION OF GEOTHERMAL SOURCES

- DETECTION OF GEOTHERMAL SOURCES WITH THERMAL IR DATA
  - REASSES FEASIBILITY OF GEOTHERMAL EXPLORATION BY USE OF THERMAL IR DATA
  - CONDUCT DATA REQUIREMENTS STUDY TO DETERMINE THERMAL CHARACTERISTICS (AT SURFACE) OF KNOWN FIELDS
  - IF REQUIREMENTS STUDY INDICATES FEASIBILITY, TEST WITH AIRCRAFT DATA

ENGINEERING GEOLOGY

- (NO RESEARCH TASKS DEFINED. PHOTOINTERPRETATIVE NATURE OF APPLICATIONS AND REQUIREMENT FOR HIGH RESOLUTION DATA RELEGATE NASA ACTIVITIES TO TECHNOLOGY TRANSFER ACTIVITIES AND TRAINING IN USE OF REMOTE SENSING DATA

6 12 6-276-2502

GEOSAT OPPORTUNITIES IN THE SHUTTLE ORBITAL FLIGHT TEST (OFT) SERIES

During the May 1976 GEOSAT (geology researcher's) meeting we were made aware that an opportunity for geologic applications/earth observations might be made available on a series of up to six (6) Orbital Flight Tests of the Shuttle commencing as early as April 1979. This was communicated verbally at the meeting by Col. Wm. Pogue of the Earth Resources Program Office (NASA/JSC) along with general characteristics of candidate sensors in a hand delivered memorandum (marked Preliminary) prepared by the Manager, Earth Resource Program, dated 4/29/76 and directed to the Deputy Director, Earth Observations Programs at NASA Headquarters.

It was also noted in the subject memorandum that it was "hoped" that because of the OFT schedule and the delivery and integration schedules of the candidate sensors (cameras), that the May meeting would result in "firm sensor requirements."

The GEOSAT committee's response to the opportunity is as follows:

All three geology industry groups (Oil/Gas, Minerals, and Engineering/Environment) have expressed a firm requirement for better than Landsat spatial resolution and stereoscopic image characteristics for applications identified elsewhere in this report.

Original Geosat OFT Recommendation write-up

ATTACH. 3 p 1 of 6

These requirements are coupled with synoptic worldwide coverage and spectral rendition of features or phenomena of interest.

Within the present state-of-the-art of space sensors which can be optimally employed on a manned spacecraft (i.e., Shuttle), a photo-optical camera and film-return can best meet these requirements.

Of the candidate cameras suggested in the subject memorandum the 12 inch focal length, 9 inch by 18 inch format camera comes closest to meeting the documented industry needs for the following three (3) basic reasons:

1) The wide-angle characteristics of the 12 in. 9 x 18 vertical system with the 18 inch format dimension along-track provides for the strongest base to height (exposure distance interval to altitude) ratio for terrain relief definition without compromising the near-orthographic (vertical) perspective. The 12 inch, 9 x 18 format permits an option of stereo overlap conditions which addresses the stated requirements of a base/height ratio of 0.4 (for high relief geological areas) to 0.9-1.0 (for exaggeration of low relief areas). This configuration is in preference to the other mapping configurations offered which compromise either the base-height ratio (18 inch f.l. 9 x 18 format) or the near vertical perspective (convergent cameras).

   Of the candidate sensors this is the GEOSAT preferred dimensional configuration. However, should other than GEOSAT applications or constraints define one of the other mapping camera configuration as optimum, the overriding requirements of resolution and stereo would still be met and the data would be employed by the geology industry.

2) From resources available at the GEOSAT meeting it was determined that the candidate 12 inch, 9 x 18 camera would provide mimimum (format corners) ground resolved distances (GRD) of 10 to 20 optically resolved meters (at low 2:1 contrast) at nominal OFT altitudes on black and white film emulsions. Although some GEOSAT GRD requirements are more severe (Engr./Envir.) it was felt that this camera system could address the majority of geologic industry applications where a geographically limited (orbit inclination constraints of OFT) three dimensional photographic data-base is required for GEOSAT.

We also understand that a true color film emulsion can be used in this candidate OFT camera. This is highly preferred by the industry as an added geologic exploration dimension even to the sacrifice of some ground resolved distances (GRD).

3) With an understanding that the OFT series of Shuttle will have a range of orbital altitudes we prefer this shorter focal length stereo mapping camera (12 inch vs. 18 inch) because of its increased cross-track coverage again without sacrificing either the strong base-height potential or the vertical configuration. From a nominal 260 km orbit altitude the 12 inch 9 x 18 "footprint" will be 194 km by 388 km.

On the negative side, both for the GEOSAT endorsement of the use of the OFT series and the candidate camera, we understand that the OFT orbit inclination will only permit coverage over a global maximum of 55°-57° North and South latitudes vs. our requirement of global coverage (see Fig.1) and that the OFT relatively short flight durations may cause some lateral gaps in terrain coverage due to the nominal altitudes and the cross-track coverage of the camera (see Fig.2). We realize that the latter can be overcome by the composite coverage of the series of 6 flights or possible follow-on opportunities on Shuttle.

Bearing on this latter problem is your offer of an additional camera type in the Panoramic Camera.

We don't feel that the coverage gap problem warrants the cost of the purchase of the more expensive (see memo) 30 inch focal length panoramic camera and since a number of GEOSAT committee members are familiar with the stereo coverage and resolution characteristics of the 24 inch focal length Lunar Pan Camera (and we assume this camera is presently in the NASA inventory) we feel its characteristics would offer a logical complement to the 12 inch 9 x 18 mapping camera since it would provide full side-lap coverage during the same OFT mission (Fig. 3) and provide both in-track and side-lap stereo. Again, a true color film emulsion would be desirable even if maximum scan angle (gap area) resolution would be somewhat sacrificed.

Summary

In summary, our GEOSAT stated requirements of stereo and resolution can be optimally satisfied in an early time-frame and of a limited geographic area by your offer of a GEOSAT photo-optical payload on the OFT Shuttle series. Our worldwide weather free coverage requirement combined with multispectral feature definition will require additional orbit characteristics and other sensors as potentially provided by both future Shuttle flights and special purpose satellites.

We recognize that the candidate camera(s) we have selected for the OFT series are not only suited to meeting a large number of geology requirements but are perhaps equally suited to topographic and cartographic applications. Topographic maps are a primary geology exploration tool and their timely and accurate preparation is very much in the interest of the geology community.

PRELIMINARY TIME SCHEDULED GEOSAT INPUT

DATE	INPUT TO	SUBJECT	SPECIFICS
3 Dec 1976	NASA	OFT-2	Investigator Proposal Due Principal Investigator Co-Investigator
Jan 1977	HOUSE	NASA	1978 Budget GEOSAT Priorities
15 Mar 1977	HOUSE	NASA	1978 Budget
After March 1977	SENATE	NASA	1978 Budget
April/May 1977	NASA	STEREOSAT	Preliminary Briefing OA Code B Cost Review
July 1977	NASA	STEREOSAT	Detailed Briefing (ER) Briefing to E, AA, AD
July 1977	GEOSAT	GEOSAT Priorities	Objective/Technology Report Due
August 1977	HOUSE	NASA	Interim 1978 Budget, 1979 Budget

Sheet 4A .. CGS - Transactions AGU Oct. 76

See also p. 741 NMAM (NAT MAG Anomaly Map)

Sheet 4B

pour parameters