IV. Geology

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INTRODUCTION

The geology session at this symposium differed from those at the three Landsat symposia in two major features.

1. Significant papers from private industry reporting applications of remote sensing to oil and gas exploration were presented. These new applications were funded by industry rather than by government contracts. This voluntary release of corporate results effectively demonstrates the practical value of remote-sensing technology. The committee recommends that this trend be encouraged and enlarged at future symposia.

2. Digitally processed Landsat images were successfully employed in several geologic interpretations. We believe this application represents a significant technologic turning point. Private discussions indicate a growing interest in digital image processing among the geologic user community.

The papers covered a wide geographic range, as shown on the index map (fig. IV-1). They also covered a wide technical and application range. At least one paper was presented on each of the following topics.

1. Oil and gas exploration, by use of radar and multisensor studies as well as by use of Landsat imagery or Landsat digital data

2. Mineral exploration, by mapping from Landsat and Skylab imagery and by Landsat digital processing

3. Geothermal energy studies with Skylab imagery

4. Environmental and engineering geology, by use of radar or Landsat and Skylab imagery

5. Regional mapping and interpretation

6. Digital and spectral methods

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OIL AND GAS EXPLORATION

Oil and gas companies have long been the major industrial users of remote-sensing imagery, but until 1975, little of their work had been revealed. In Volume II, Sabins points out that the pressure of exploration work, rather than company security, prevents many petroleum geologists from presenting their work.

Radar Applications

At a gas field in which production was from a "tight" sandstone reservoir (with the most productive gas wells located where the sandstone is naturally fractured), Owens and Ryan reported that radar imagery was the most effective method for locating surface fracture and fault zones. The 15 wells drilled on the basis of this information proved to be twice as productive as the average field wells.

Another successful radar application involved regional and local studies in Indonesia (G-1, vol. I-B). In the low relief part of the basin, a major arch and a drainage anomaly were mapped; both should merit detailed investigation. Two different types of folds were mapped in the foothills region. Long, narrow, sinuous folds probably do not persist at depth, but terminate at thrust faults. The radar imagery distinguished a second and more favorable fold type exemplified by the giant Dusseldorf anticline; these are relatively gentle folds that should persist at depth. In this rugged jungle area with poor weather for aerial photography, radar imagery provided a clear view of the terrain. Potential exploration targets were defined so that expensive field and seismic work could be concentrated on the most promising areas. Any oil discoveries in this area would probably be credited to geophysics despite the key role played by remote sensing.
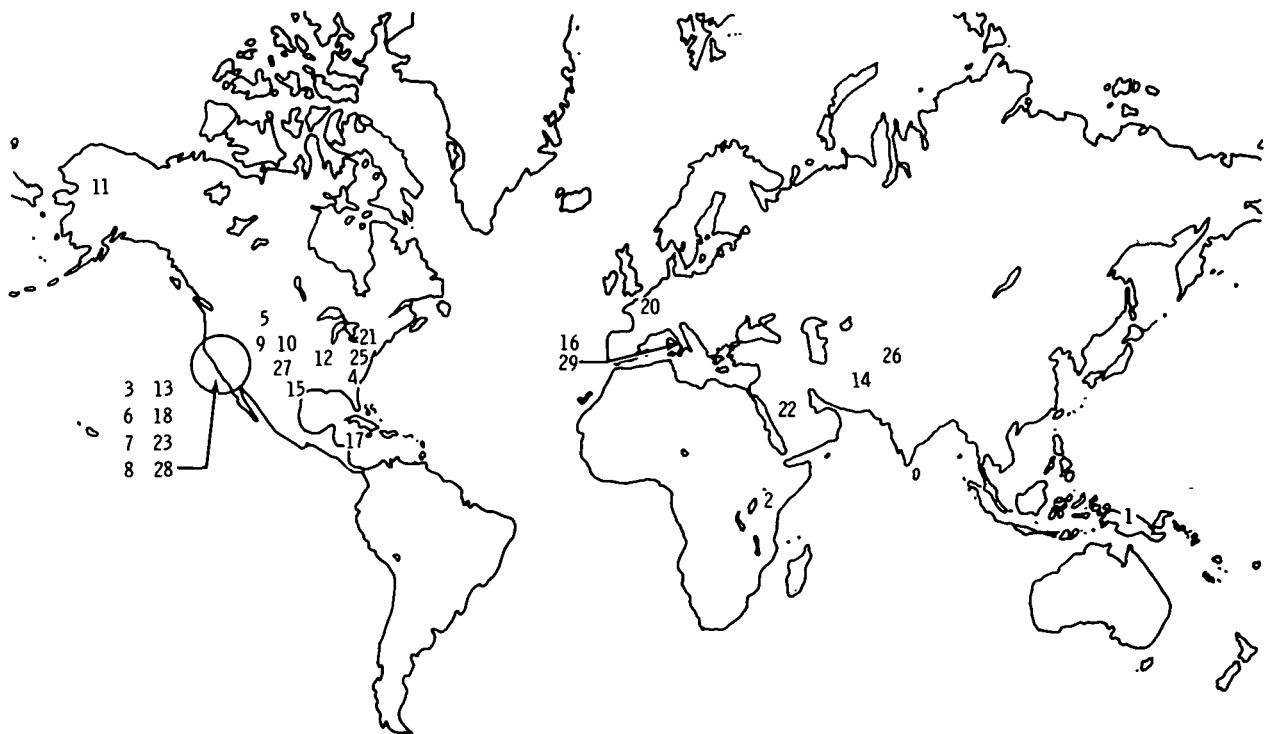
Figure IV-1.- Geographic distribution of papers presented in geology panel.

Landsat Applications

A major oil company found an area worthy of drilling on the basis of Landsat imagery. In another instance, a different oil company acquired an exploration area based largely on Landsat interpretation (G-2, vol. I-B). The investigator compared the Landsat results with his earlier interpretation of conventional aerial photographs. The lineaments defined on Landsat imagery were clearer, more continuous, and more extensive than those on the aerial photographs. The Landsat lineament pattern appeared to define a sedimentary basin, which was confirmed by subsequent geophysical work. A surprising amount of lithologic and geomorphic information was also obtained from the imagery.

Exploration Potential

Four papers demonstrated a variety of oil exploration uses of remote-sensing imagery. Some nonindustry people have questioned the value of remote sensing in general and of Landsat in particular because "it has not found any oilfields." As Sabins indicates in Volume II of the proceedings, no single technique can reveal oilfields;

Landsat imagery has only been available for a short time, and the greatest use is for reconnaissance studies to indicate anomalies for detailed field and geophysical investigations. The economic value of Landsat for exploration should not be judged by "how many oilfields it has found" but rather by the fact that industry purchases large volumes of data and assigns valuable manpower to its interpretation.

MINERAL EXPLORATION

Analysis of Landsat multispectral scanner (MSS) images has resulted in development of two techniques having considerable potential for augmenting conventional mineral exploration methods: (1) delineation of landforms, especially linear and generally circular features, that may be the morphologic expression of important crustal features, and (2) detection of hydrothermal alteration zones, which represent the surface expression of potential ore deposits. Although these approaches to mineral exploration had been discussed previously, their potential has been reinforced by the results of this symposium.

Conventional Imagery for Landform Studies

The value of satellite images and photographs for detecting large-scale linear and circular features has been recognized for more than a decade, but adequate evaluation of these features has been complicated by several factors, including their horizontal and apparent vertical extents, the subjectivity of the basic data, and the complexity of their surface expression and origin. Consequently, the usefulness of this approach to mineral exploration has been the subject of debate. However, field evaluation has shown that some of these linear features are zones of crustal weakness; many others undoubtedly have similar origins. In general, circular features are less enigmatic than linear features; most circular features are intrusive or volcanic. Some very large circular to elliptical features are of undetermined origin, and these may be especially critical to the distribution of ore deposits.

Before this symposium, most mineral exploration papers inferred the relationships of known ore deposits to linear and circular features. In other words, the results were general rather than specific. At this symposium, two papers described the occurrence of ore deposits along the traces of specific lineaments. More importantly, one of these studies identified a mineral prospect that warrants further evaluation. Through evaluation of lineaments mapped on MSS images of eastern Nevada (G-28, vol. I-B), 17 favorable targets were selected for mineral exploration. Field studies of 11 of these areas suggest that 7 have favorable structural and alteration features, and semiquantitative spectrographic analysis of selected limonitic samples showed anomalously high arsenic, molybdenum, copper, lead, zinc, and silver content. Although these faults are shown locally on available geologic maps, their regional extent was defined in the Landsat lineament studies.

The second paper (G-21, vol. I-B) described detailed field studies in Pennsylvania of a series of widely spaced northwest-trending lineaments found in Landsat imagery. This terrain and the surface expressions of the lineaments contrast sharply with those in Nevada. Statistical analysis of field data shows that brecciated rocks are concentrated in the lineament zones. In many places along the lineaments, limonitic staining is present. Mineralization is not widespread in this region, but lead and zinc deposits appear to be localized along some of these apparent fracture zones. Although considerably more work is needed to define the origin of these features, early speculations indicate that they are vertical, crustal fracture zones, which are at least as old as the late Paleozoic era.

Geophysical data as well as geological evidence are being used more widely to determine the geologic significance of lineaments. Pascucci correlated aeromagnetic and gravity data with Landsat data showing lineaments to define promising target areas. This combined geophysical and Landsat analysis is important in exploring for ore deposits concealed beneath the alluvium that covers approximately 50 percent of the area.

Although Skylab photographs are being used less extensively than MSS images in mineral exploration, a circular feature in California visible on Skylab imagery was described (G-7, vol. I-B). It has the topographic, structural, vegetation, and color anomalies that are typical of some mineralized zones, especially copper porphyry deposits. The topographic expression is seen best in Skylab S190A and S190B color photographs obtained when light snow cover was present, but the feature is detectable in other Skylab photographs and in MSS images.

Digitally Processed Imagery for Detecting Hydrothermal Alteration

Detection of hydrothermal alteration zones in MSS images depends on slight spectral reflectance differences between altered and unaltered rocks. Although these differences are apparent in visible and near-infrared (0.4 to 2.5 micrometers) reflectance spectra, they are subdued by the positions and the widths of MSS bands. Despite these and other limitations, several workers have shown that alteration zones can be mapped in MSS images. Because of the subtleness of these spectral differences, however, digital processing of a computer-compatible tape (CCT) has been necessary for detecting most alteration zones. In general, conventional MSS color-infrared composite images and Skylab color photographs have not proved useful for this particular application.

Two papers described different approaches to detecting and mapping hydrothermal alteration zones using Landsat CCT data. Approximately 80 percent of the anomalously colored outcrop areas in a color-ratio composite proved to be related to hydrothermal alteration, Rowan, Ashley, and Goetz indicated. Subtle color differences among the altered areas appear to be due to slight mineralogical variations.

Outcrops of pink hematitic tuff and limonitic shale and siltstone were erroneously identified as altered rocks because of reflectance similarities in the MSS spectral

response ranges. At wavelengths near 2.2 micrometers, there are reflectance differences that should distinguish the tuff from altered rock. The ferruginous shale and siltstone, however, have a reflectance spectrum nearly identical with that of the altered rock, and the possibility of discriminating these rocks is slight.

In a two-stage study (G-26, vol. I-B), a known hydrothermally altered, sulfide-bearing copper porphyry deposit was used as a reference area for identifying other altered areas. The first stage of the study was based on evaluation of very high quality Landsat color-infrared composites. Seven candidate targets were identified and checked in the field. No significant alteration was found in any of these areas, confirming previous experiences of other workers using color-infrared composites for this purpose.

Machine processing of the digital radiance values was used in the second phase of analysis to develop a classification scheme. A classification map was prepared, and 30 targets were selected as being spectrally similar to the reference area. Nineteen of these areas were visited in the field. Of these, five are altered quartz-feldspar porphyry and contain 5 to 10 percent pyrite, an indication that these areas may be porphyry copper deposits. The Pakistan government is now conducting a detailed evaluation of these areas.

Although these two approaches to mapping alteration zones have significant differences, they are complementary rather than competitive. In most cases, the most effective approach will probably be a carefully tailored combination of enhanced-image interpretation for compiling alteration maps of large areas and of digital classification for detailed analysis of specific altered areas.

Research Needs

Although the feasibility of these techniques for mineral exploration has been demonstrated, more research is needed to bring them to the operational stage. The most critical need in both cases is development of models that take into account the large number of variables encountered in different geologic and environmental settings. Studies are underway for refining and expanding existing spectral reflectance models for commonly occurring rock types, especially alteration products. Because of the subtlety of the spectral reflectance differences among rocks and the relative importance of other factors, quantitative models will ultimately be required for reliable application of this technique on an operational basis.

Models are also essential for analyzing linear and circular features, but quantification is difficult at this stage because of limited understanding of the origin of these features. However, as specific types of features are identified, models should be developed to describe their distinguishing geologic and geophysical characteristics.

ENVIRONMENT AND ENGINEERING GEOLOGY

High-resolution aerial photography has been used for years for engineering geologic applications, such as establishing sites for large construction projects. More recently, such photography has been useful in preparing environmental geology maps. Additionally, other types of remote sensing, such as side-looking airborne radar imagery and satellite imagery, have been used increasingly in these two areas.

Environmental Geology

Aerial photography at various scales was used to construct a series of environmental geology maps and physical property maps for the State of Texas (G-27, vol. I-B). These maps show surface features such as rock and soil cover, drainage, slope stability, location and properties of building materials, and roadway routing. They are currently being used by state agencies in Texas.

Engineering Geology and Identification of Geologic Hazards

Use of Landsat-1 imagery has been recommended in helping plan new highway routes (G-12, vol. I-B). The imagery was used successfully to map a northern Arkansas lineament complex which correlates well with landslide-prone areas along major highway routes in the area.

In a similar application (G-14, vol. I-B), Landsat-1 data were used to map lineaments and to identify possible faults in areas being considered as sites for nuclear powerplants. Substantial savings to clients were cited because sites identified as containing faults were not included in expensive ground surveys.

An investigator (G-11, vol. I-B) used side-looking airborne radar data acquired through the NASA Earth Resources Aircraft Program to identify probable flood scour features near the area where the trans-Alaskan pipeline is to cross the Yukon River. The features are

located at elevations on the banks higher than floodwaters are known to reach and raise a question as to the statistical frequency of occurrence of floods that might be expected to cause such features and thus cause a problem for the pipeline.

Nearly simultaneous rupturing of water mains in two Pennsylvania towns is believed to be related to activity along two lineaments and a fault identified on Skylab and Landsat imagery (G-21, vol. I-B).

Findings from studies of faults (G-13, vol. I-B) on Landsat and Skylab imagery could be important in identifying areas prone to future earthquakes. Investigators using Landsat, Skylab, and aircraft imagery identified several faults near the NASA Lyndon B. Johnson Space Center that appear to have been activated by the withdrawal of underground water and are believed to be related to subsequent subsidence in the area (G-15, vol. I-B).

These results relate the importance of remote sensing in identifying geologic hazards and in providing information to environmental and engineering geologists. They also indicate that, although high-resolution photography remains the primary method for acquiring remotely sensed information for these purposes, increasingly smaller scale orbital imagery can provide useful information in a cost-effective manner.

MAPPING AND INTERPRETATION

Lithologic Identification

Earlier reports on the use of satellite images revealed a general inability to identify and distinguish most rock types. Spectral response curves for many common rocks do not contain enough characteristic narrow wavelength "peaks and troughs" (as, for example, does X-ray analysis) to permit ready discrimination of different rock types. The properties recorded by cameras or scanners in the visible to near-infrared wavelengths are essentially colors and brightnesses, or spectral reflectances, which simply do not show enough correlation with mineral composition and textures to allow accurate recognition of most major rock types. Thus, light-colored sandstones, limestones, tuffs, and even granites would produce similar tones in photographic images. Adequate recognition of rock types is largely confined to those having distinctive or unique albedos or colors (e.g., basalts) or to those occurring in characteristic terrains or settings (e.g., some granitic intrusives).

Several papers described the problems of making useful rock identifications by conventional photogeologic techniques. Certain alluvial and eolian deposits, regionally homogeneous sediments, basalts, and coarse-textured crystalline massifs have been identified in vegetation-deficient, arid terrain (G-22, vol. I-B). Investigators concluded, however, that this limited selection was insufficient for effective geologic mapping. In another study, it was noted that red outcrops are not necessarily related to weathered sulfide-bearing rocks, but could be volcanic or sedimentary rocks (G-10, vol. I-B).

The greatest recent advances in rock identification have been in the computer processing of Landsat MSS digital data. Work by Rowan, Ashley, and Goetz using the VICAR program developed at the NASA Jet Propulsion Laboratory to make contrast-stretched and band-ratioed color composites is leading the way. Multiple and hybrid ratio and contrast-stretched images from VICAR processing were used to enhance a broad color anomaly related to higher iron content in Tertiary continental sediments (G-5, vol. I-B). This anomaly was significantly affected by variations in topography, by local exposure of a red sandstone, and by changes in vegetation types and densities. On the digitally processed images, this iron-related anomaly could be clearly distinguished from one caused by deep red siltstones of Triassic age. At least one variant of the VICAR program is also in use.

Stratigraphic Boundaries

One essential aim in geologic mapping is the accurate location of accepted stratigraphic boundaries. The limitations of rock identification and the low resolution of space imagery together imply that the production of such maps would be difficult at a level of specificity required to mark the boundaries accurately. However, both Landsat and Skylab images have been used to improve or edit many small-scale maps for such types of boundary relationships as the contacts of igneous intrusives, basalt flows, dikes, and some thick sedimentary sequences.

Boundaries of a granitic intrusive on a color-ratio composite image were compared with those on a published map and the conclusion was made that the intrusive is larger than had been mapped (G-22, vol. I-B). More precise boundaries can now be drawn. Other investigators (G-7, vol. I-B) used Skylab S190B photographs to better outline the boundaries of a poorly mapped circular feature having a well-defined

topographic expression. The Triassic Chugwater red beds were found to have a distinctive color in color-ratio composite images (G-5, vol. I-B); this color distribution does not coincide with the Chugwater outcrop shown on aerial photographs or on the state geologic map. Field studies show this discrepancy is caused by spectrally similar red colluvial soils extending beyond the Chugwater outcrop limits.

Geomorphic Features

No systematic study of landforms was given at this symposium. However, various investigators illustrated the continuing use of remote-sensing imagery in recognizing, describing, and, analyzing geomorphic features. For example, workers using Landsat images have been able to map coalescing alluvial fans (G-2, vol. I-B) and to acquire information on other alluvial landforms (for example, G-9, vol. I-B). Erosional changes along the Atlantic coast were monitored by Landsat. A 3-mile-long island, not shown on maps made 25 years ago and presumably newly formed, was "discovered" in band 7 images. From Landsat images, Pickering mapped more than 1000 Georgia lakes with geometric and geographic characteristics that suggest they belong to the swarm of Carolina Bays farther north. The alinement trends and occurrence of slight rims on the south sides (as seen from the ground and from aerial photographs) suggest a meteorite impact origin. Skylab images assisted (G-16, vol. I-B) in recognition of paleo-riverbed channels in the Italian Po River plains.

Structural Relations

In the three Landsat symposia and at many professional meetings since the launch of the two Landsat and the Skylab spacecraft, most geologic papers described detection of linear features from space. Those features not caused by man were generally identified with structural faults, fractures, and lineations. The geology sessions in this Earth resources symposium were marked by a notable reduction in linears as the primary feature observable from space. Much less was said about the simple recognition and charting of linears. Instead, more emphasis was placed on linears as geologic structures, on criteria for their identification, on problems in objective selection of "genuine" lineations, and on regional implications of the numerous newly discovered extensive linear features.

Investigators described the effects of operator subjectivity and of machine processing in identifying linears on Landsat scenes (G-19, vol. I-B). Using an Australian study as a model, each of four geologists at the NASA Goddard Space Flight Center (GSFC) mapped linears from the same scene in western Oklahoma. A wide disparity in selecting the same linears resulted: all four operators found only 4 of 785 linears in common; three chose 37 in common; two selected the same 140; and the remaining 604 linears were identified by one or another of the individuals. The total number and the average length selected by an individual also varied extensively, but broadly similar orientation trends were observed by all four in common. The linears picked by GSFC operators agreed with only 30 percent of those drawn by an oil company in its study of the same area. This company has reported only 35 percent coincidence of linears mapped from Landsat images with those seen on Skylab images. These examples of variability (largely related to subjectivity in selection) indicate that a set of recognition criteria are needed to minimize "false alarms" and misclassifications. Some automated procedure may be needed to remove operator subjectivity from the selection process. An analog system using an enhanced television display of a Landsat transparency achieves some measure of objectivity. In another approach, a digital enhancement program is used to provide an image display that minimizes directional effects.

Criteria were defined for field recognition of 16 long linears that extend across central Pennsylvania (G-21, vol. I-B). These criteria include (1) breccia zones, (2) fractured and slickensided rocks, (3) gossans and other types of iron and/or manganese staining, (4) sulfide mineralization, (5) stratigraphic offsets, and (6) anomalous water flows from springs and seeps.

Aeromagnetic and gravity contours from maps were converted into trend lines. The coincidence of these geophysical trend lines with linears appearing on Landsat imagery was then checked by statistical tests. A high positive correlation was determined; furthermore, 60 percent of the mineral deposits in the study area are associated with linear and trend line coincidences.

Elston and Dipaolo found three major orthogonal directions of lineament pairs on Landsat, Skylab, and RB-57 images of Arizona. The most abundant and prominent lineaments are identical with the trends of major Precambrian faults and transect terrain underlain by Paleozoic and Tertiary strata. This indicates that the lineaments reflect basement structures that were periodically reactivated.

Various papers illustrated the advantage of space imagery for locating circular features and curvilinear trends. The several origins proposed suggest that significantly different types of circular features occur. Investigators (G-10, vol. I-B) noted arcuate fracture systems that seemingly relate to intrusive structures. Others (G-17, vol. I-B) found new curvilinear traces that probably outline volcanic centers. Some of these features are caused by active tectonism; others may be caused by subsidence following withdrawal of ground water or petroleum.

Following the Earth resources symposium, an interesting map was shown by Dr. A. Jackson, principal investigator of Landsat imagery for Lesotho (an enclave within South Africa). From 4 images, more than 13 000 linears that correspond to short dolerite dikes intruded into basalt flows were mapped. Where stereographic overlap and sidelap strips were examined, the number of linears nearly doubled. This observation offers strong justification for including stereographic capability in future satellites, particularly those dedicated to geologic applications.

SUMMARY

In 1975, the Kansas and Texas symposia demonstrated the increase in applications of remote-sensor imagery by industry. Not only Landsat and Skylab imagery but that resulting from older methods such as radar and thermal-infrared imagery and aerial photography are being applied practically. Industrial users should increase the publication of their results to help justify continuation of the U.S. remote-sensing programs.

Another trend in 1975 was toward applications beyond conventional geologic mapping. These applications include recognition of landslide hazards, identification of active earthquake faults, and siting of nuclear powerplants.

A pronounced trend toward geologic application of digital processing of Landsat data, especially for mineral exploration, was evident. Both ratio imaging and multispectral classification were successfully demonstrated in test areas that were probably ideal. In moving from the experimental Landsat program to application satellites, particular attention should be given to the optimum spatial and spectral resolution and to the spectral range. This emphasis is necessary to achieve successful applications in areas that are less than ideal.

WORKSHOP

After the formal papers were presented, 125 workshop participants discussed problems and future requirements for applying remote-sensing technology to geology.

Linears

The often controversial subject of linears and lineaments received much attention. Numerous faults on geologic maps are not identified on Landsat and other remote-sensor imagery. Conversely, many linears on the imagery do not correlate with mapped faults. On the positive side, a number of new faults have been discovered on Landsat imagery, even in regions that have been thoroughly mapped. Several excellent individual investigations of Landsat-identified linears have been reported, but a systematic evaluation of linears expressed on different scales and types of imagery in different geologic terrains is clearly needed. Computer-assisted statistical methods should aid the objective analysis of linear studies. The following needs exist.

1. Objective methods for recognizing and classifying linears

2. Definition of optimum imagery properties (scale, resolution, and spectral bandwith) for linear recognition

3. Systematic evaluation of geologic significance of linears

Digital Image Processing

The U.S. Geological Survey, NASA facilities, universities, and commercial organizations are developing and applying computer technology for digital image processing. The processing is predominantly applied to Landsat images which are available in computer-compatible tape format. Noise removal, banding correction, haze removal, geometric correction, and contrast enhancement provide optimum images for the interpreter. Color composites of ratio images and multispectral classification are more advanced techniques. The expense and limited availability of the image processing systems have restricted the application of these techniques to geologic problems. Development of relatively inexpensive interactive processing systems should be accelerated.

Spectral and Spatial Resolution

Color-ratio composites and spectral classification techniques are potentially powerful exploration methods for recognizing surface alteration associated with ore deposits. The low spatial resolution of Landsat relative to the heterogeneity of geologic terrains is a handicap to this application. The Landsat spectral bands are not optimum nor do they extend far enough into the near-infrared region for maximum definition of rock, mineral, and alteration signatures. We urgently need a spectral signature library of these targets (measured in the field, not the laboratory) for two reasons: (1) to analyze existing multispectral imagery and (2) to define optimum spectral regions for future sensor systems.

Radar Imagery

Radar imagery for geologic applications is presently confined to the K- and X-band regions (1- to 3-centimeter wavelengths) and has been very useful for structural studies in heavily vegetated terrain and areas of persistent cloud cover. The L-band region (25 centimeters) may also have significant geologic application. Before satellite deployment, more aircraft L-band imagery is needed for evaluation.

Relationship of NASA and Geologic User Community

In response to constructive suggestions from the workshop, a representative of the NASA Office of Applications stated that NASA policy is to consider carefully research suggestions from the earth-science community that include clear, reasoned geologic requirements supported by feasibility studies and experiments. NASA planners note, however, that geologic opinion is divided on several subjects affecting applications, such as linears; this leaves NASA planners confused as to the needs of the geologists.

This apparent division among geologic users of remote-sensing imagery results from the diversity of geologic problems. Geologists use remote-sensor imagery for mapping lineaments ranging in scale from continent-wide down to less than a mile. Petroleum geologists map entire sedimentary basins searching for potential oil structures measured in miles; mining geologists examine specific mineral belts for areas of rock alteration only a few acres in extent. Regional mappers are content with scanner images analogous to color-infrared photographs; those using digital processing need narrow spectral bands and data that extend farther into the infrared region where significant spectral signature differences occur. Geology is the most technically diversified user discipline, and no single combination of scale, spatial resolution, and spectral range and resolution will meet all of these requirements.

Recommendations

The following recommendations were made.

1. A definitive investigation of linears and lineaments that includes imagery expression correlated with surface and subsurface data should be designed and conducted.

2. In the field of digital image processing, development of relatively inexpensive interactive systems is required to make the technology more widely available.

3. Collection of a library of field reflectance spectra of geologic targets should be accelerated. These spectra are needed to design future imaging systems and to interpret existing multispectral data.

4. A definitive experiment on spatial resolution requirements for different geologic applications is also needed to define future imaging systems.

5. Longer wavelength radar imagery (L-band) should be acquired and made available to the geologic user community for evaluation and application. This is essential training for the forthcoming satellite radar imaging systems.