Ground-Water Applications of Remote Sensing

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U.S. Department of Interior
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EROS Data Center
Sioux Falls, South Dakota

GROUND-WATER APPLICATIONS OF REMOTE SENSING

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GROUND-WATER APPLICATIONS OF REMOTE SENSING

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ABSTRACT

Remote sensing can be used as a tool to inventory springs and seeps and to interpret lithology, structure, and ground-water occurrence and quality. Thermograms are the best images for inventory of seeps and springs. The steps in aquifer mapping are image analysis and interpretation and ground-water interpretation. A ground-water interpretation is derived from a conceptual geologic model by inferring aquifer characteristics and water salinity. The image selection process is very important for obtaining maximum geologic and hydrologic information from remotely sensed data.

Remote sensing can contribute an image base map or geologic and hydrologic parameters, derived from the image, to the multiple data sets in a hydrologic information system. Various merging and integration techniques may then be used to obtain information from these data sets.

INTRODUCTION

Remote sensing is the use of reflected and emitted energy to measure the physical properties of distant objects and their surroundings. Thus, remote sensing is a source of basic data, a science, and a tool. The measurements, whether recorded on a strip chart, magnetic tape, or film, are the data. Remote sensing is a science because the relative and absolute measurements can be analyzed and interpreted to yield meaningful conclusions. It is a tool because the conclusions can be used to inventory resources and to monitor and

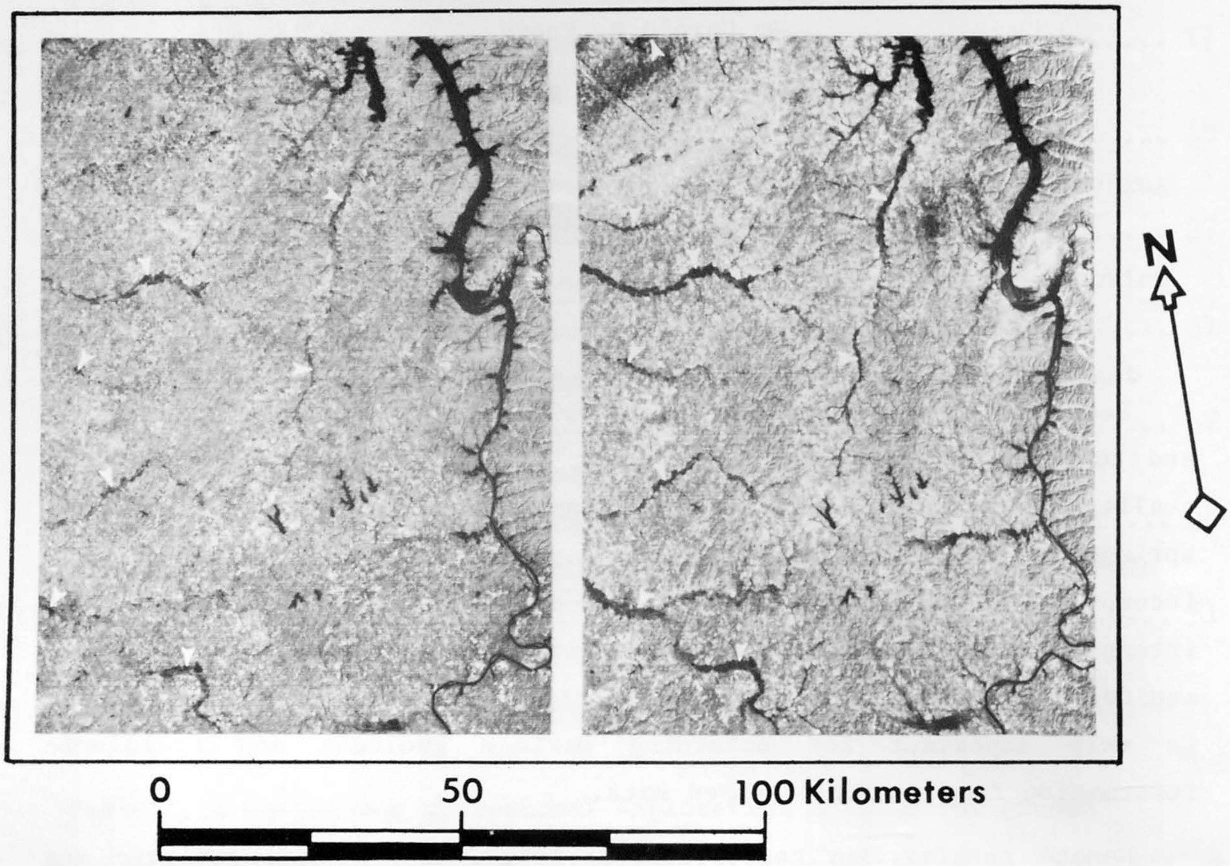


Figure 1.--Dark gray to black tones along stream valleys in coastal plain sediments indicate saturated soils caused by a high water table. National Aeronautic and Space Administration (NASA) near-infrared Landsat images E-5185-15305-7 (left) and E-2371-15462-7 show parts of the Tennessee, Hatchie, Forked Deer, Obion, and Big Sandy River drainage systems in western Tennessee on October 21, 1975 (left), and January 28, 1976.

study ecological problems. Remote sensing includes the older sciences of photography, photograph interpretation, photogrammetry, and airborne geophysical surveying, as well as newer techniques that use other parts of the electromagnetic spectrum.

This report describes the operational use of remote sensing for ground-water exploration. A comparison of exploration methods (tables 1 and 2) shows that remote sensing is a fast and inexpensive method of obtaining some ground-water information. In some cases, remote sensing may also result in information that cannot be obtained by other methods. Many papers in the literature, for example, show that an interpretation of satellite images has provided new insight into the geology and hydrology of areas that previously had been mapped on the ground. A third use of remote sensing is to select promising areas for other exploration methods. Finally, remote sensing is the only practical method of recording transitory soil-moisture (fig. 1) and vegetation-phenology patterns over large areas.

Limits to the types and amounts of information that can be obtained by remote sensing are determined by surface cover and near-surface characteristics. In heavily vegetated regions, for example, remote sensing provides mainly structural information, although general lithologies and the presence of a shallow water table, springs, and seeps can be inferred from landform, drainage, vegetation, and temperature patterns. Other limits are imposed by the spectral characteristics and spatial resolution of remote sensing instruments. Some landscape features have a distinctive signature in only a small part of the electromagnetic spectrum.

Two other limits to the use of remote sensing are data acquisition conditions and the need for interpretation and inference. Repetitive, remotely sensed data are rarely identical because of differences in antecedent and atmospheric conditions. Thus, a scientist generally determines the significance of relative differences in the data rather than using absolute values. The importance of data selection is described later in this report. Exploration for ground water by remote

Table 1.--A comparison of regional exploration methods for ground water

Method	Procedures	Personnel Requirement	Area Coverage Rate	Results
Interpret satellite images or mosaic.	Analyze tones, textures, shapes, patterns, location and association.	One scientist, in office.	3,000 to 34,000 km^2/day	Interpretation of lithology, structure, and ground-water occurrence based on landforms, drainage patterns, land use, soil tones, and vegetation types and patterns.
Geologic reconnaissance.	Examine lithologies, orientations, and fracture patterns.	One scientist, in field.	250 km^2/day	Generalized geologic map and sections showing lithology, stratigraphy, and structure.
Hydrologic reconnaissance.	Inventory largest wells and springs. Examine rock types, orientations, and fracture patterns.	One scientist, in field.	100 km^2/day	Generalized hydrologic map showing aquifers, aquitards, and areas of recharge and discharge.
Magnetic prospecting.	Measure differences in the Earth's magnetic intensity.	One scientist and one pilot for aerial studies.	250 to 2,500 km^2/day	Calculation of sedimentary rock thickness and interpretation of basement structure.
		One scientist and one helper for ground studies.	2.5 to 250 km^2/day	
Gravity prospecting.	Measure differences in the Earth's gravitational force.	One scientist, one surveyor, and two helpers.	2.5 to 250 km^2/day	Interpretation of shallow structures and lateral changes in rock density.

Table 2.--A comparison of local exploration methods for ground water

Interpret aerial photographs.	Analyze tones, textures, shapes, patterns, location, and association.	One scientist, in office.	100 to 500 km^2/day	Interpretation of lithology, structure, and ground-water occurrence based on landforms, drainage patterns, land use, soil tones, and vegetation types and patterns.
Detailed hydrologic mapping.	Inventory all wells and springs. Determine nature of ground-water occurrence. Determine aquifer characteristics.	One scientist, in field.	10 km^2/day	Information on ground-water occurrence, well yields, and water quality. Description or model of targets for test drilling.
Detailed geologic mapping.	Examine lithologies, orientations, and fracture patterns. Trace contacts.	One scientist, in field.	2.5 km^2/day	Detailed geologic map and sections, showing lithology and structure and based on rock outcrops, soils, and vegetation.
Electrical prospecting.	Measure Earth's electrical potential and resistivity.	One scientist and two to four helpers.	2.5 to 12 km^2/day	Interpretation of vertical stratigraphy, lateral changes in lithology, and structure (including locations of rock fractures).
Shallow test drilling.	Soil auger or jetting rig.	One scientist, one driller, and two helpers.	0.5 to 5 km^2/day	Lithology, porosity, and permeability of unconsolidated materials.
Deep test drilling.	Cable-tool or rotary rig and geophysical logs.	One scientist, one driller, and two helpers.	0.1 to 1 km^2/day	Lithology, porosity, and permeability of subsurface materials. Well yield and aquifer characteristics.

sensing is always indirect and depends on an interpretation of landscape patterns. However, a consideration of the exploration methods in tables 1 and 2 indicates that all methods depend on interpretation. A geologist thus infers the presence, depth, and attitude of lithologic units between outcrops and test wells.

The accuracy of results obtained by interpretation of remotely sensed data depends on the knowledge, experience, and skill of the scientist. So, however, do results of all other geologic and ground-water exploration methods. A well-known scientist (W. D. Hardeman, Tennessee Department of Conservation, oral commun. 1964) once said, "Any geologic map is a progress report." At best, in other words, it shows the most logical interpretation of all available facts and evidence. Remote sensing should be used for ground-water studies as a supplement to conventional procedures and not as a replacement. Nevertheless, the processing and interpretation of remotely sensed data can produce considerable ground-water information. This information should make possible a better and more accurate progress report on the ground-water resources of many areas; total time and cost for the study should also be less than if carried out entirely by conventional techniques.

Remote sensing offers the greatest economic benefits when used near the beginning of a project. The initial study of these data generally should precede fieldwork. The advantages of an initial remote sensing study (Ray, 1960, p. 14) include (1) reduction in the need for field surveys in some areas, (2) direction of attention to anomalous areas where detailed field studies are needed, and (3) provision of a basis for organizing the fieldwork.

At later times in a project, information that is obtained at a point on the ground commonly may be extended over an area by reference to remotely sensed images. Also, similar objects and features may be found elsewhere. The maximum benefit from remotely sensed data is obtained by a coordinated use of these data and other sources of information, including published reports and detailed field studies.

This report contains recommendations on the types of images that produce best results for particular hydrologic objectives. The

Figure 2.--Springs are small features and are difficult to detect on aerial photographs. Each of these two springs near Murfreesboro, Tenn. is discharging more than 600 liters per second of water from solution cavities in the limestone bedrock. The color photograph was obtained by U.S. Geological Survey on April 23, 1973, after a period of heavy rain. The photograph also shows a number of shallow sinkholes filled with muddy water.

recommendations are based on experience with common landscape and image characteristics, but they are not intended to be all-inclusive. Other remotely sensed data may produce good results for other study objectives or for special landscape conditions.

SPRINGS AND SEEPS

Remote sensing techniques can produce faster and cheaper inventories of springs and seeps than ground survey techniques. However, only spring locations can be determined; water discharge rates must be measured or estimated on the ground. Most springs and seeps are small targets for remote sensing and are obscure on panchromatic black-and-white and color aerial photographs (fig. 2). Other techniques must be used under carefully selected conditions.

In arid regions, the presence of many springs and seeps is indicated by anomalous snowmelt, soil moisture, or vegetation patterns. Snowmelt patterns show the combined results of all heat sources, including solar, atmospheric, and terrane sources. If everything else is equal, snow melts first in areas where ground water is at or near the surface. Vegetation may also begin an earlier growth in these areas. A few anomalous snowmelt patterns, apparently produced by shallow ground water, can be seen on color-composite Landsat MSS (multispectral scanner) images, but more accurate interpretations are possible with aerial photographs. The early greening of vegetation is more obvious on color-infrared photographs on which the pink to red or reddish brown hues of living vegetation are unique (fig. 3). Although some springs and seeps are indicated on these images by snowmelt patterns, repetitive photography during the melt period is necessary.

Soils are darker where they have a high moisture content, and different types or densities of vegetation may occur in these areas (fig. 3). In arid regions, high-altitude color-infrared photographs generally have adequate resolution to detect the lines and areas that indicate seeps and springs. Large areas are also visible on Landsat MSS color-composite images (fig. 4). Landsat images acquired near the end

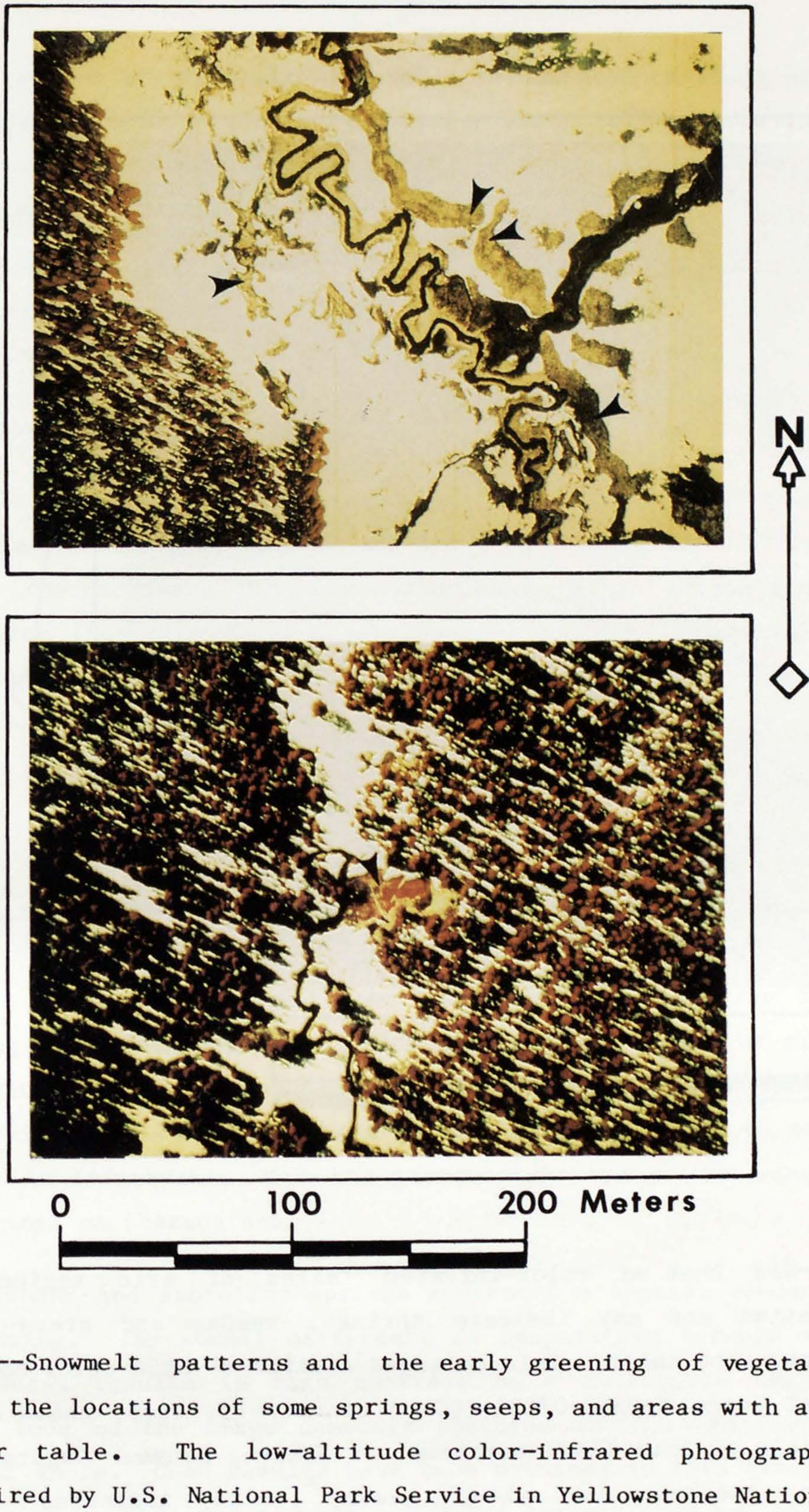


Figure 3.--Snowmelt patterns and the early greening of vegetation may show the locations of some springs, seeps, and areas with a shallow water table. The low-altitude color-infrared photographs were acquired by U.S. National Park Service in Yellowstone National Park on June 5, 1974.

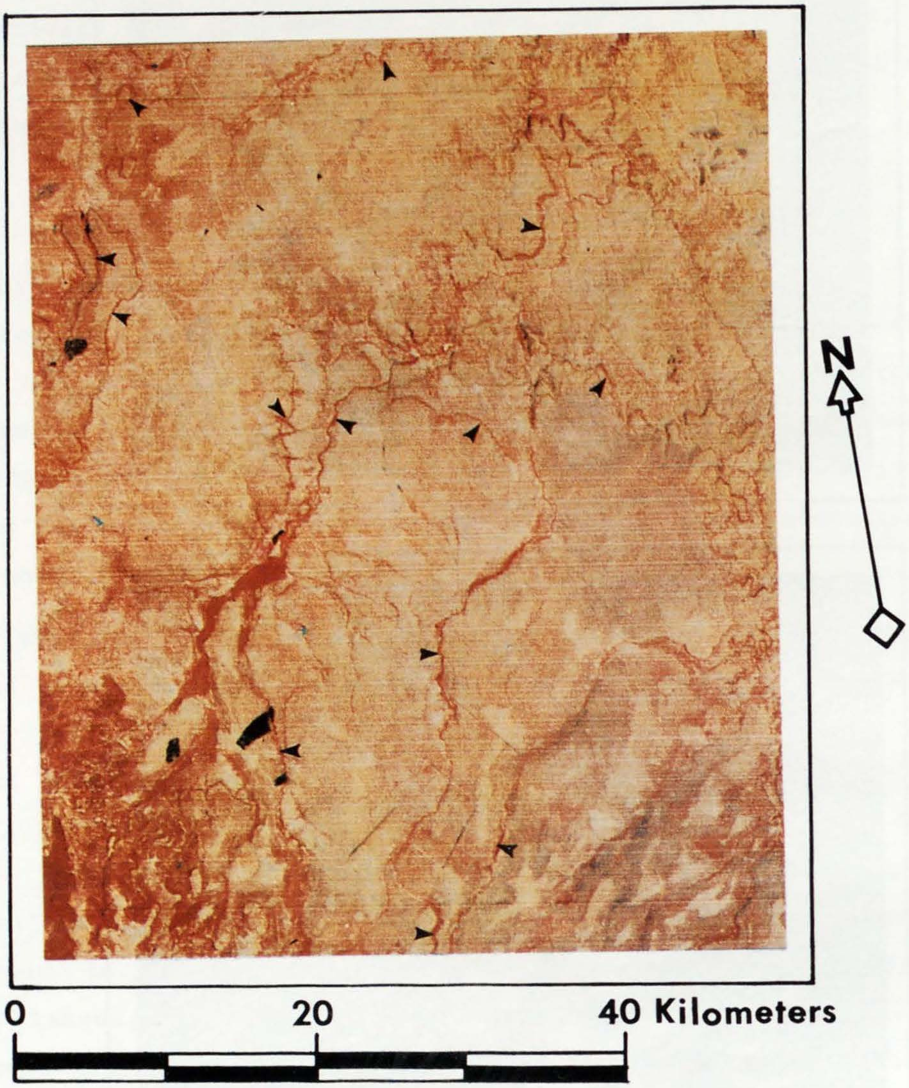


Figure 4.--Red hues on color-infrared images of arid regions show vegetation and may indicate springs, seeps, and areas with a shallow water table. This enlarged section of NASA color-composite Landsat image E-2368-07031-FCC on January 25, 1976, shows an area underlain by lava flows northeast of Nakuru, Kenya. Vegetation in valley bottoms and along valley walls indicates tubular permeability in the basalt flows or between flows.

of the wet season are commonly used for a reconnaissance study of spring and seep areas in arid regions. Vegetation along valley sides in figure 4 indicates ground-water discharge by seepage, as well as tubular permeability in the underlying basalt flows.

The presence of vegetation in arid regions may also indicate discharge of ground water by transpiration from riparian vegetation and phreatophytes. Thin lines of riparian vegetation generally are visible only on aerial photographs, but most phreatophyte areas can also be seen on Landsat images.

The best remote sensing technique for inventory of seeps and springs is thermography (thermal-infrared images), but special conditions are necessary at the time of acquisition. Night flights at low altitudes (for high resolution) during unusually cold weather have produced best results (fig. 5). A leafless condition also is necessary in deciduous forests (fig. 6). Night flights may cause aircraft navigation problems but avoid the effects of solar heating during the day. Day flights beneath a high overcast have also produced good results.

Thermal scanners are sensitive to differences in infrared emittance of about 1° C, but small-area anomalies are easier to detect when the temperature contrast is large. Location of spring discharge is a hot spot during midwinter and can be detected as a white line or area in a gray background on the thermogram. Shallow ground-water temperatures in the conterminous United States have a range from 7° to 27° C, and a 20° C contrast in temperature with the surroundings has proven adequate to detect springs on thermograms.

Streambank and shoreline springs represent a special situation for remote sensing. The normal difference in temperature between land and water surfaces results in high contrast on a thermogram image; this change in tone on the image commonly obscures springs and seeps along the bank or shore. Good results have been obtained in this situation by selecting a time when land and surface-water temperatures are nearly the same (fig. 7). Ground-water temperatures may be either warmer or

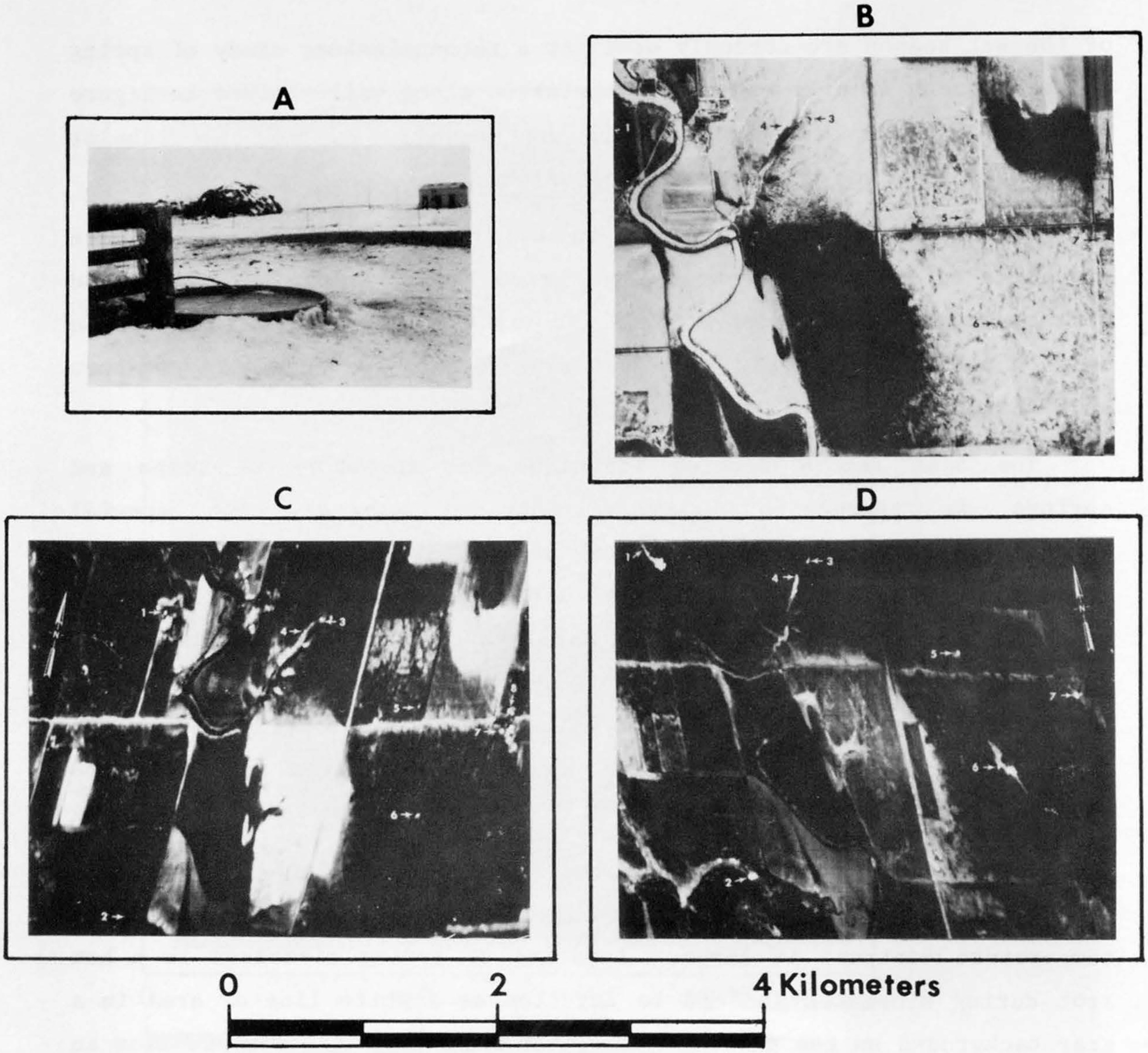


Figure 5.--A predawn thermogram (fig. 5D) shows flowing wells and springs better than a daytime thermogram (fig. 5C) or an aerial photograph (fig. 5B) in northern Beadle County, S. Dak. (Moore and Myers, 1973). Photographs and images were obtained by Remote Sensing Institute, South Dakota State University on February 12, 1971. Ground surface temperatures were about -10° to -20° C. Springs (locations 1 and 2), flowing wells (locations 3, 5, 6, and 7), and a stock tank (fig. 5A, location 4) had water temperatures of 11° to 34° C. Aircraft altitude was about 3,000 m above terrane.

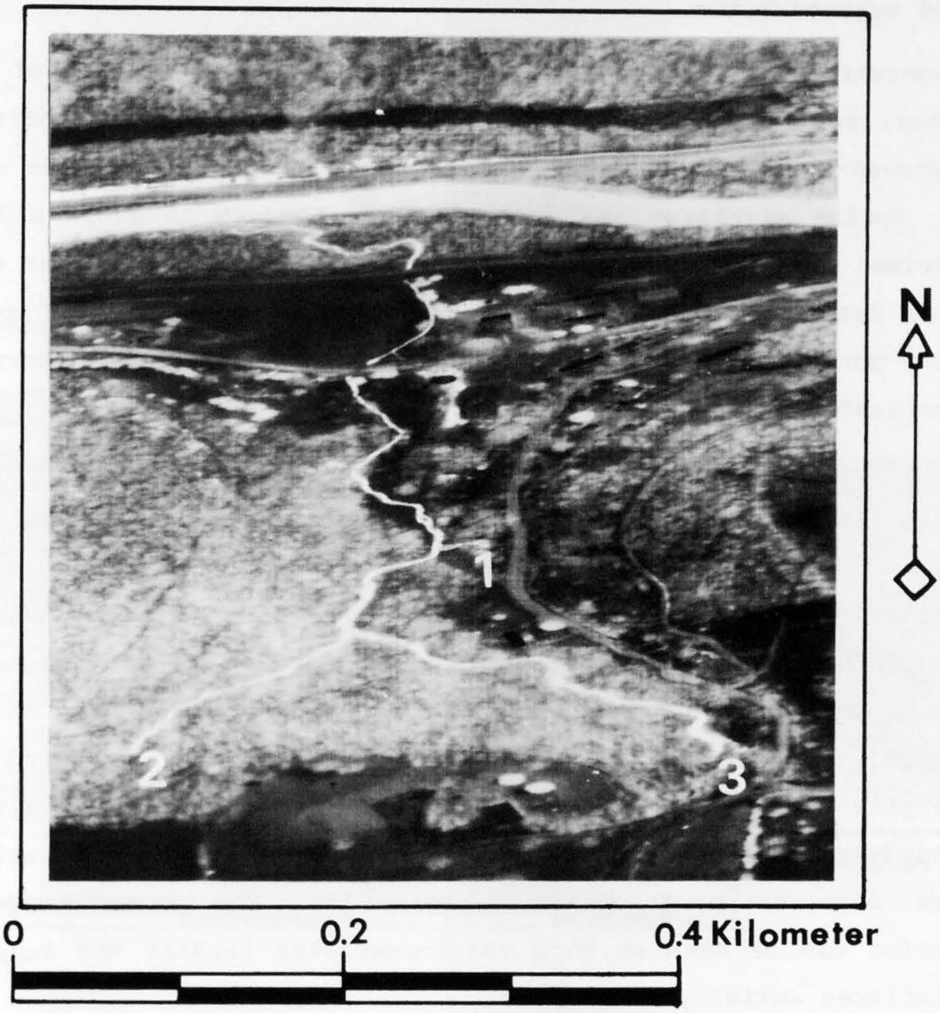


Figure 6.--A nighttime thermogram shows springs in a surface mining region near Fairmont, W. Va., on March 18, 1978. A deciduous forest cover is leafless at this time of year. The thermogram was obtained at an altitude of about 600 m above terrane by U.S. Environmental Protection Agency.

colder, but this temperature contrast should be larger than that between land and surface water.

Underwater springs (ground-water discharge at the bottom of a lake or stream) must rise to the surface to be detectable on a thermogram. Thus, ground-water temperature must be warmer than that of the surface water. Spring discharge must also be large enough to avoid a loss of this thermal contrast by mixing and dispersion. Some underwater springs are also detectable on aerial photographs because of water color or turbidity patterns. A shallow and clear surface water is necessary, and this combination is unusual in inland waters.

Many springs and seeps in humid regions can be mapped by soil moisture, land use, and vegetation differences. Narrow or less obvious zones of high soil moisture content are best detected on low-altitude color or color-infrared photographs acquired during the wet season (fig. 8). Areas that remain wet for longer periods of time are not used for crops and may have a distinctive vegetation cover (fig. 9). Near the Gulf Coast, for example, brush or deciduous trees grow in spring areas, whereas pine forests occupy the better drained uplands. Also, a hemlock and rhododendron vegetation association occurs on cold, wet sites in the southern Appalachian Mountains (fig. 10). The latter vegetation association can be seen on both color-composite Landsat MSS images and color-infrared aerial photographs.

AQUIFER MAPPING

Panchromatic black-and-white (minus blue) aerial photographs have been used as an aid to hydrogeologic mapping for many years; the principles of this use are well established and documented in the literature (Avery, 1977, Mollard, 1972, Ray, 1960, and Way, 1973, for example). Remote sensing has contributed infrared films, high-altitude aerial photographs, and the multispectral, repetitive, synoptic (regional) view of satellites to an image data base for ground-water exploration. Landsat MSS images are used as the main example of information content in the following discussion, because these images have worldwide availability in both film and digital formats.

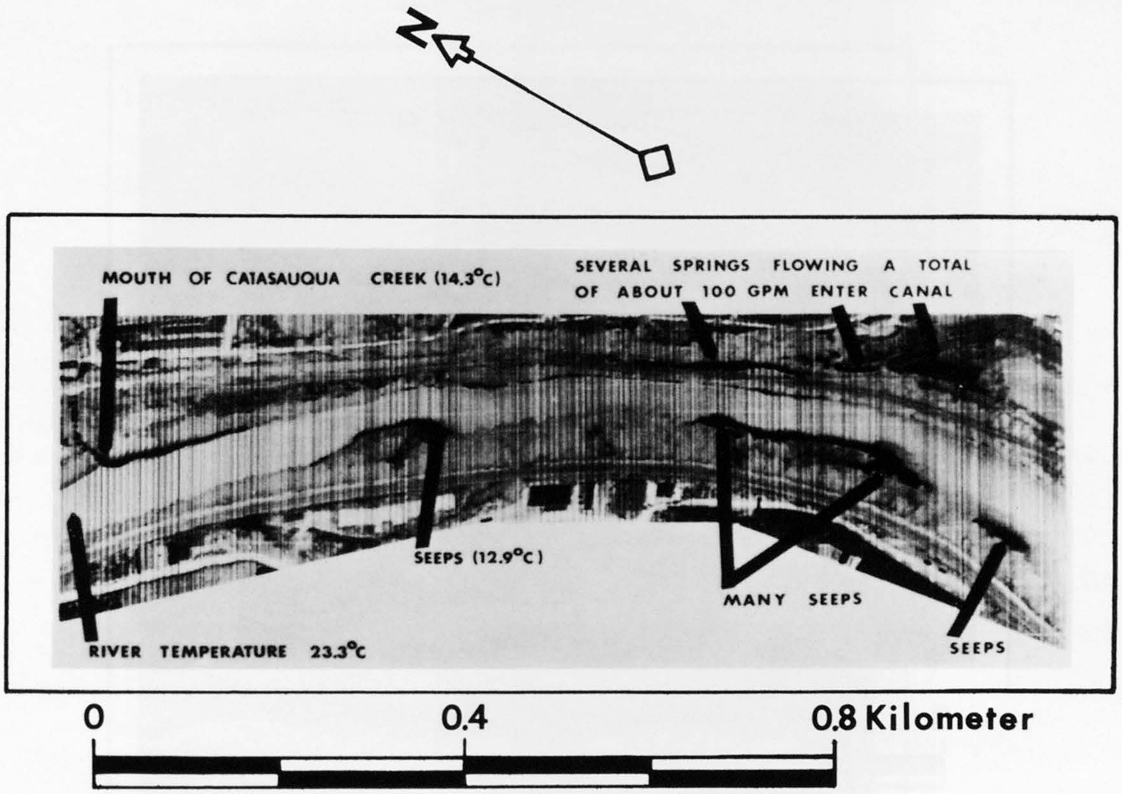


Figure 7.--Streambank springs are easily detected on thermograms when land and surface-water temperatures are nearly the same. This predawn thermogram of the Lehigh River at Allentown, Pa., was obtained by NASA on August 1, 1968. River and land temperatures were 22° to 26° C; temperatures of the springs and seeps were 10° to 15° C (Wood, 1972, p. 347).

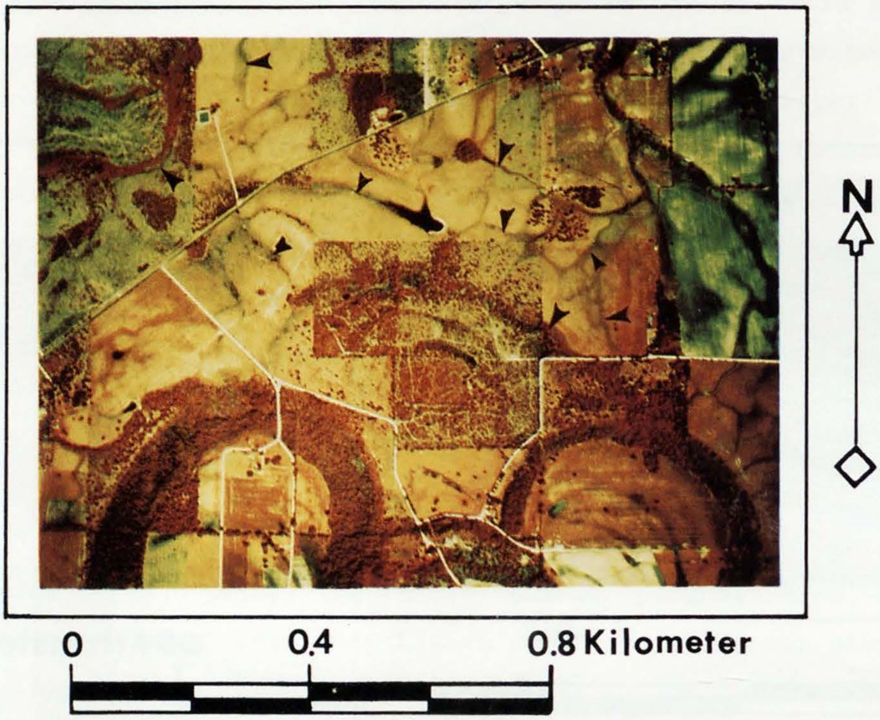


Figure 8.--Patterns of vegetation and soil tone show seeps and other areas of high soil moisture in coastal plain sediments. This color-infrared photograph near Picayune, Miss., was obtained by U.S. Geological Survey in April 1973.

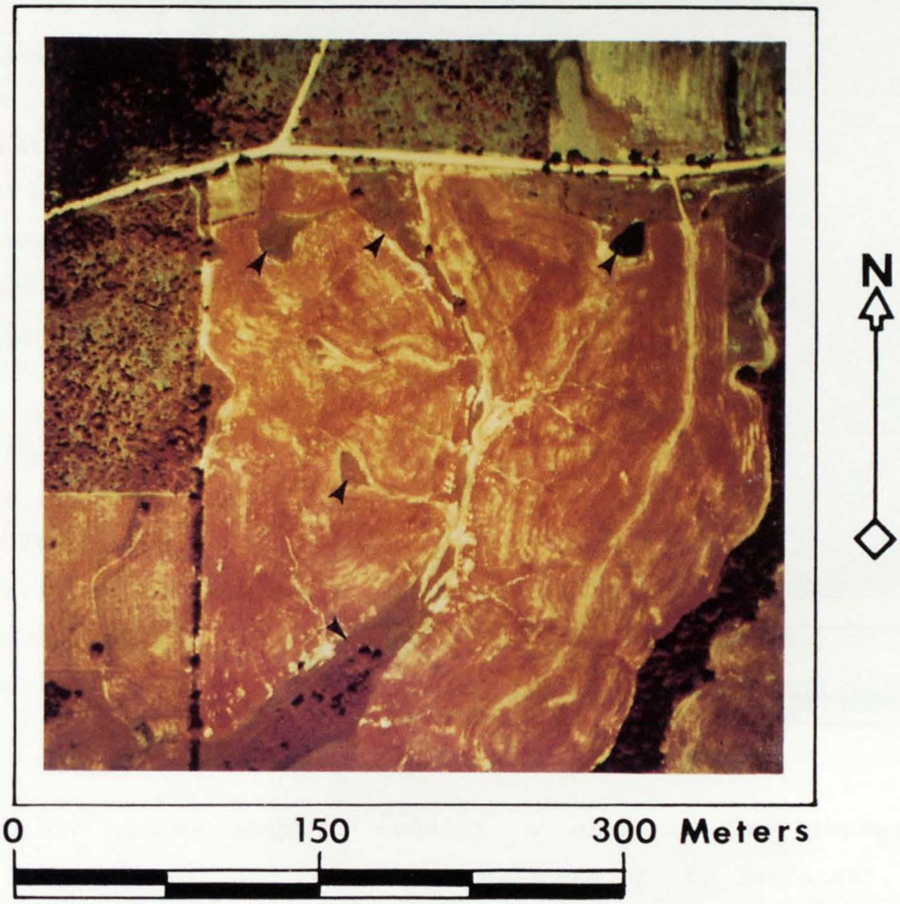


Figure 9.--Brush and deciduous trees grow in wet spring and seep areas, whereas the better drained uplands are used for agriculture and pine forest. This color-infrared photograph near Picayune, Miss., was obtained by U.S. Geological Survey in May 1973.

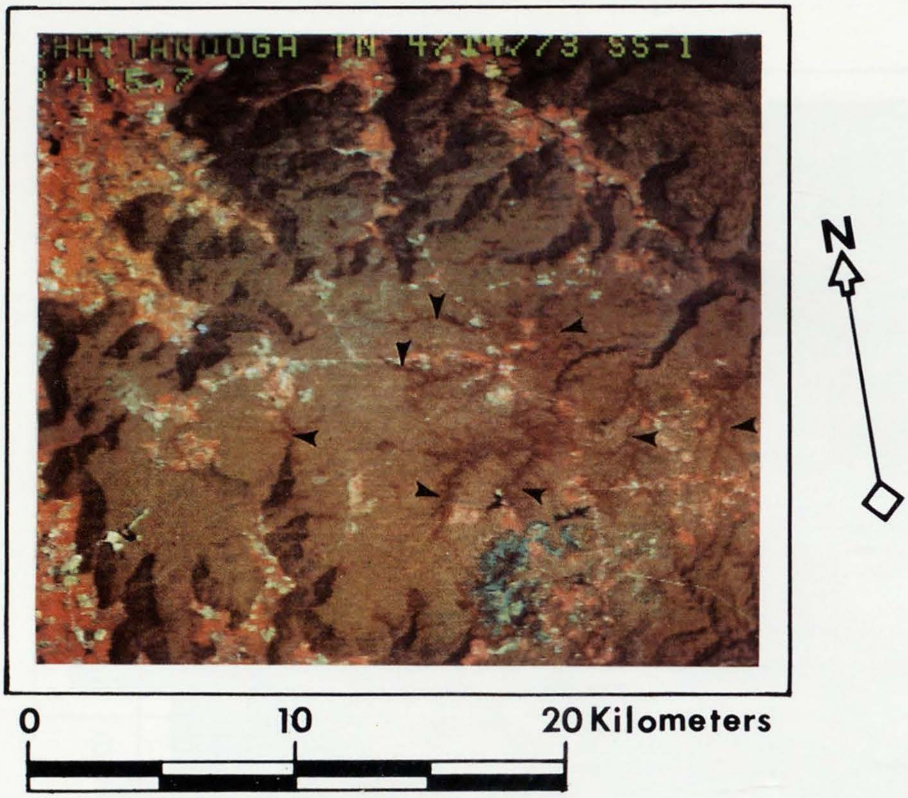


Figure 10.--The maroon color in some stream valleys shows a hemlock and rhododendron vegetation association and indicates cold, wet sites. This section of NASA color-composite Landsat image E-1265-15501 shows parts of the Highland Rim and Cumberland Plateau between Tracy City and McMinnville, Tenn., on April 14, 1973. Deciduous trees on the Cumberland Plateau are dormant at this time.

A common mistake in the use of remote sensing is to assume that all ground-water information can be obtained from a single data set. Aerial photographs and Landsat images are complementary sources of information. Each source of data having a different spectral band or spatial resolution can contribute to the knowledge of an area. Small landscape features can only be detected on low-altitude, high-resolution aerial photographs. The low resolution of satellite images, however, actually aids the interpretation of regional features, because less cultural detail is visible to distract the eye of the interpreter. Regional features are also more likely to be detected on small scale images because they fall more nearly within the interpreter's field of view or field of cognizance. Further, many topographic and land cover boundaries which are gradational on the ground appear sharp on satellite images.

Image analysis and interpretation may be separate or simultaneous. A trained scientist may be able to select favorable test well locations after only a few minutes of image study. However, a systematic procedure is recommended to document interim results and to avoid errors of omission. The steps in such a procedure are image analysis, image interpretation, geologic interpretation, and hydrologic interpretation.

Image Analysis

Remotely sensed images consist of elements that represent the physical, biological, and cultural components of the landscape. Groups of similar elements represent similar conditions. Image analysis consists of detection and classification of these similar groups. The results of image analysis are objective land cover and physiographic (elevation or aspect) classes.

An image may be analyzed visually or by computer processing of digital image data. Computer analysis is called classification but includes the equivalents of detection and delineation. Visual image analysis is based on tone (or hue), texture, pattern, size, shape, location, and association. Computer analysis uses digital values, which are the equivalent of tone or hue; a few algorithms also use some measure of texture (the spatial variability of tone). Computer processing is faster, objective, and results in more accurate separations of spectral reflectance than visual analysis, but visual analysis generally results in fewer land cover classification and delineation errors. Spectral and spatial classes must be identified to produce land cover maps.

Multispectral data from cameras, scanners, television systems, or solid-state linear arrays of detectors are necessary for accurate land cover mapping. Landsat MSS data can be used to map level 1 and some level 2 (Anderson and others, 1976) land use and land cover classes. Accuracies average about 80 percent but range from 90 to less than 50 percent, depending upon the complexity of local conditions, the time of image acquisition, and the method of analysis. Visual analysis of Landsat MSS data is most efficiently done from a color-composite image. A MSS near-infrared (0.8-1.1 m wavelength) black-and-white image is also useful, especially for mapping shallow water and saturated soil areas.

Land cover maps which show areas of bare soil, rock, and vegetation, are hydrologically useful. The spectral signatures of these areas and image patterns may indicate: (1) areas of saline soils, (2) differences in surface lithology, (3) ground-water seeps and springs, and (4) areas having a shallow water table. Lithologic differences in bare soil and bare rock areas are best detected on color-infrared aerial photographs and color-composite Landsat images. Visual analysis of spectral signatures is common, but computer processing of digital image data produces more accurate and credible results. Differences in tone (and hue) are the most important single factor in soil discrimination (U.S. Soil Conservation Service, 1966, p. 47-48). Except in recently eroded areas, however, remotely sensed images show only weathered rock surfaces and surface soil types.

Elevation or aspect classes are easily mapped by computer processing of digital topographic data. Alternatives are visual analysis of satellite images and aerial photographs.

Image Interpretation

Image interpretation is the visual and subjective grouping, delineation, and identification of landscape characteristics, based mainly on shapes and patterns. Results of this interpretation are maps showing landforms, drainage nets, other drainage characteristics (pattern, density or texture, basin shape, and channel position), lineaments, and curvilinears.

Landforms can be simply defined (American Geological Institute, 1972) as recognizable "physical features on the Earth's surface, having a characteristic shape, and produced by natural causes. * * * Taken together, the landforms make up the surface configuration of the Earth." Some definitions also include the geomorphic origin or the material composition of landforms; such inferences are useful for geologic interpretation but are unnecessary for image interpretation. It is important to recognize that the delineation and labeling of landforms are subjective procedures. Different results are obtained by outlining individual features or a group of features and by delineating an asymmetric ridge rather than the adjacent asymmetric valley, for example.

Landforms and drainage lines are more easily and completely identified by stereoscopic viewing. An alternative is monoscopic viewing of images with a relatively low Sun-elevation angle--so that small-scale topographic relief is enhanced by shadowing. A thin snow cover produces a uniform white background for topographic shadowing; landforms and drainage lines are more apparent on these images. Thick snow obscures some fine topographic detail and some land use and land cover information. Landforms can also be studied on shaded relief maps produced by computer processing of digital topographic data.

Drainage lines are shown on topographic and many planimetric maps. However, several tests have shown that more drainage lines may be visible on Landsat MSS images than are shown by a combination of blue lines and contour cusps on 1:250,000-scale topographic maps. Similarly, more drainage lines may be visible on aerial photographs than are shown on 1:24,000-scale topographic maps. It should not be assumed that all available information on drainage characteristics can be obtained from existing maps.

Lineaments are defined (O'Leary and others, 1976, p. 1467) as "mappable, simple or composite linear features of a surface, whose parts are alined in a rectilinear or slightly curvilinear relationship and which differs distinctly from the patterns of adjacent features and presumably reflects a subsurface phenomenon." Lineaments may be assumed to be fractures during a geologic interpretation. As defined, however, lineaments are features with obscure origins and significance, and presumptions of significance should not be made during the image interpretation process. Other image lines that are interpreted as faults, foliation, stratigraphic contacts, or other outcrop patterns should be separately mapped and identified.

Lineaments on the land surface are formed by a variety of landscape elements, including topographic, drainage, vegetation, and soil tonal alinements. Some lineaments are continuous, and many others appear to be continuous, because closely spaced edge and line segments are merged by the human eye. A careful examination of the images, however, shows that most lineaments are discontinous in detail.

During the usual lineament interpretation process, a scientist examines an image for closely spaced linear segments that appear to be alined. This process is subjective, and results depend mostly on the scientist's experience and on the purpose for the interpretation. Comparison of operator results in one study (Podwysocki and others, 1975, fig. 4) showed that "only 0.4 percent of the total 785 linears were seen by all four operators, 5 percent by three operators, and 18 percent by two operators." The same study also found significant differences in the average lengths of lineaments mapped by different scientists. The patterns obtained by different operators should be similar, but wide variations occur in lineament locations and densities. Thus, lineament maps that have not been field checked are always controversial.

Various objective approaches to lineament enhancement, extraction, or delineation are possible with digital processing of image-format data (for example, Ehrich, 1979, Burdick and Speirer, 1980, and Podwysocki and others, 1975). These approaches include directional filters (ordinarily implemented by a convolution procedure), edge-enhancement algorithms, filtering of Fourier transformed data, and various line-detection and line-follower algorithms. Currently, however, there is not a completely objective procedure for lineament extraction and mapping.

Another problem in lineament mapping is biases introduced by illumination direction and data characteristics. Lineaments with trends near the illumination direction are partly obscured, whereas lineaments with trends at angles of 60° to 120° from this direction are maximally enhanced. Landsat images have a southeasterly solar azimuth in the northern hemisphere, and lineament frequency diagrams generally show a northwesterly minimum and a northeasterly maximum. Another bias is caused by the nearly east-west scan lines on a Landsat MSS image; image interpreters tend to ignore features that have nearly the same trend as the scan lines. Finally, some digital image enhancement algorithms have directional properties. An edge-enhancement algorithm used at Earth Resources Observation Systems (EROS) Data Center, for example, enhances northerly trends more than easterly trends. Directional biases are minimal during stereoscopic viewing of aerial photographs.

Smoothly curved lines and edges, such as those with circular and arcuate shapes, are curvilinears. These features are rare on images of most geologic terranes but may be common in coastal plains and in areas of doming and igneous intrusion. Curvilinears are discontinuous in detail, and are subjectively mapped. They generally are presumed to be evidence of igneous rocks or of domes, basins, and other folds during a geologic interpretation.

Selection of the best images for detection of lineaments and curvilinears is partly a matter of personal preference. Radar images, where available, are used for this purpose, but results are biased by the antenna look direction and depression angle. Many scientists prefer Landsat MSS near-infrared images and black-and-white infrared aerial photographs, because vegetation and other cover patterns are not prominent and distracting on these images. On Landsat images, topographic lineaments are enhanced by a low Sun-elevation angle and by a thin snow cover. Alinements of soil tone and vegetation generally are most easily detected on color-infrared photographs.

Shaded relief maps are an alternative data source for the mapping of topographic lineaments. Directional biases can be minimized by producing three images, with simulated illumination of the terrane at three 120° azimuth angles. A difference in topographic relief in an area is compensable by producing images at selected elevation angles for the simulated illumination. The latter problem is thoroughly discussed for the case of radar antenna depression angles by MacDonald and Waite (1971).

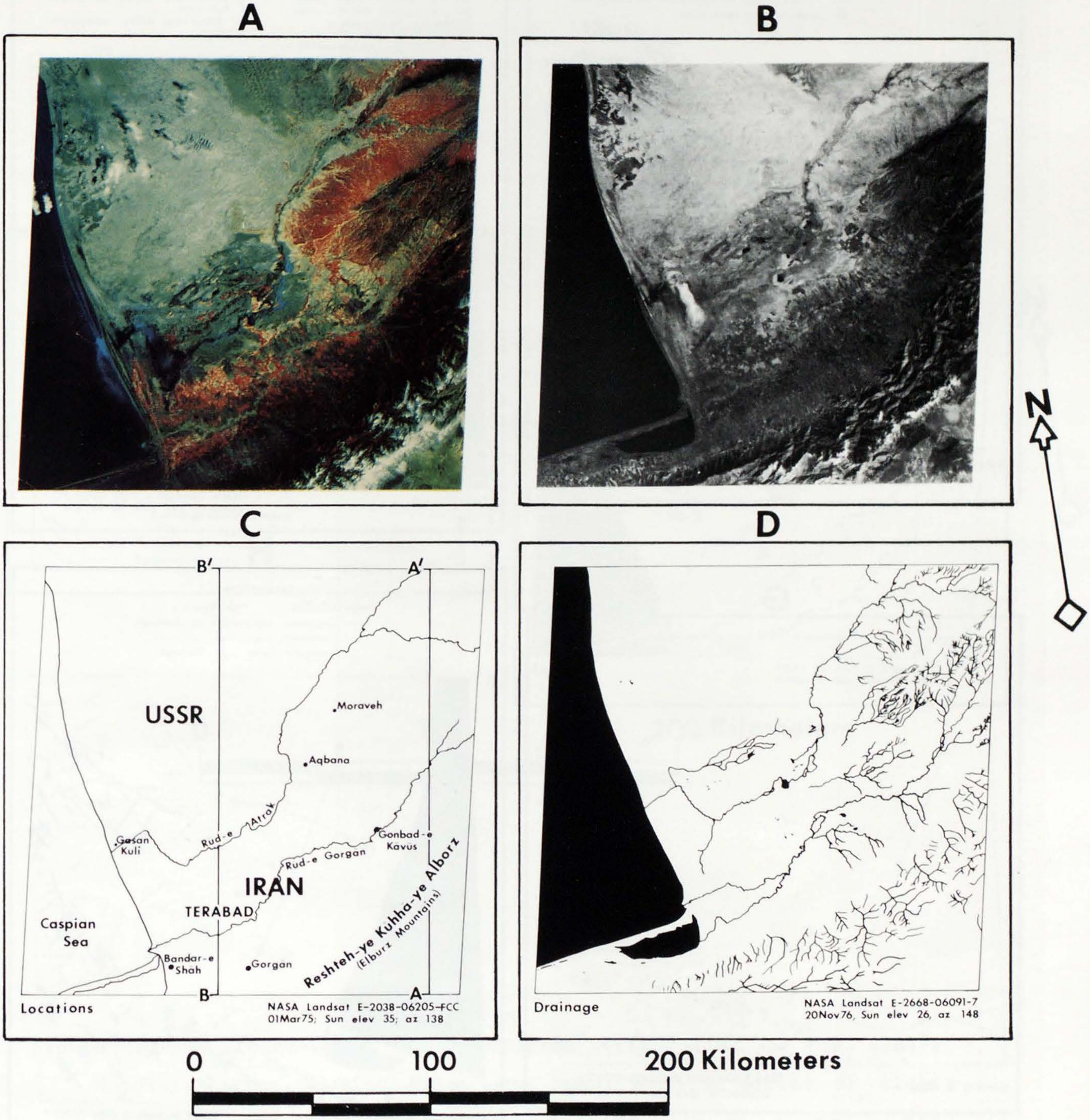
Geologic Interpretations

A geologic interpretation includes four elements or phases (Taranik and Trautwein, 1976, p. 29) which depend on the relationship between surficial landscape features and the processes that produced these features:

1. An interpretation of surficial lithology, stratigraphy, and structure.
2. An interpretation of surficial geomorphic processes.
3. An interpretation of subsurface geologic relationships.
4. An interpretation of sedimentary, diagenetic, metamorphic, igneous, and tectonic processes.

A complete geologic interpretation develops a three-dimensional conceptual model which explains the results of image interpretation. The model may also indicate the possibility of additional geologic features; the detection of such features on the image or on the ground is partial confirmation of the model.

In developing a conceptual model, it is important to separate facts and assumptions and to recognize various degrees of reliability in


A
B
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Gasan Kuli
Rud-e Atrak
Gonbad-e Kavus
Rud-e Gorgan
IRAN
TERABAD
Caspian Sea
Bandar-e Shah
Gorgan
Reshteh-ye Kuhha-ye Alborz
(Elburz Mountains)
B
A
Locations
NASA Landsat E-2038-06205-FCC
01Mar75; Sun elev 35; az 138
Drainage
NASA Landsat E-2668-06091-7
20Nov76, Sun elev 26, az 148
0
100
200 Kilometers

Figure 11.--

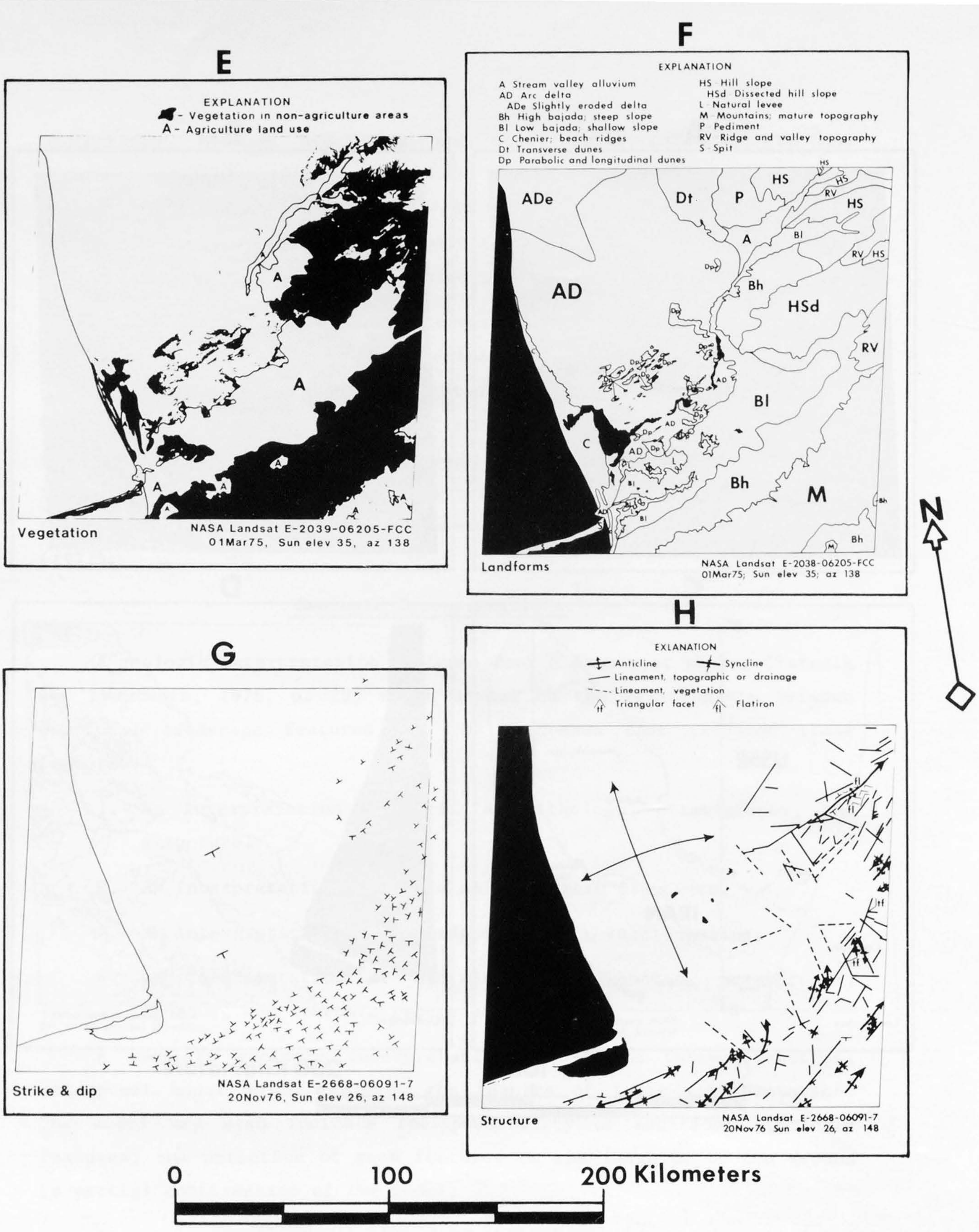
E
EXPLANATION
- Vegetation in non-agriculture areas
A - Agriculture land use
Vegetation
NASA Landsat E-2039-06205-FCC
01Mar75, Sun elev 35, az 138
F
EXPLANATION
A Stream valley alluvium
AD Arc delta
ADe Slightly eroded delta
Bh High bajada; steep slope
Bl Low bajada; shallow slope
C Chenier; beach ridges
Dt Transverse dunes
Dp Parabolic and longitudinal dunes
HS Hill slope
HSd Dissected hill slope
L Natural levee
M Mountains; mature topography
P Pediment
RV Ridge and valley topography
S Spit
Landforms
NASA Landsat E-2038-06205-FCC
01Mar75; Sun elev 35; az 138
G
Strike & dip
NASA Landsat E-2668-06091-7
20Nov76, Sun elev 26, az 148
H
EXLANATION
Anticline
Syncline
Lineament, topographic or drainage
Lineament, vegetation
Triangular facet
Flatiron
Structure
NASA Landsat E-2668-06091-7
20Nov76 Sun elev 26, az 148
0
100
200 Kilometers
N

Figure 11.--

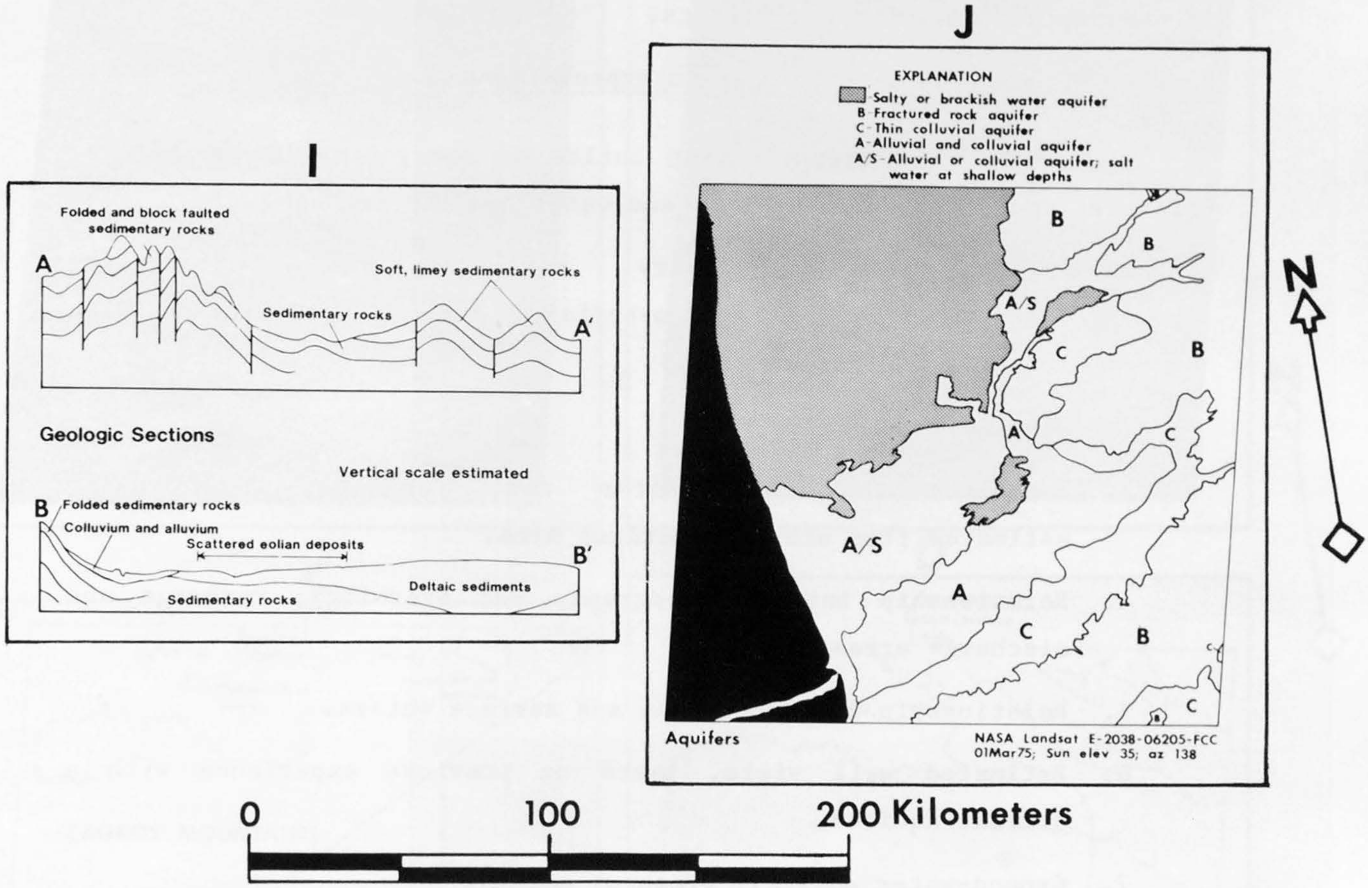

Figure 11.--A ground-water interpretation (fig. 11J) of the Elburz Mountains area, Soviet Union and Iran, used a series of eight overlays. The image interpretations (figs. 11C, D, E, and F) and geologic interpretations (figs. 11G, H, and I) were made from NASA Landsat images E-2038-06205-FCC on March 1, 1975 (fig. 11A), and E-2668-06091-7 on November 20, 1976 (fig. 11B).

results of the interpretation procedures. By making these distinctions, it is relatively easy to revise the model or the interpretations if they do not produce satisfactory results.

Hydrologic Interpretations

A ground-water interpretation builds on the conceptual geology by inferring aquifer characteristics and water quality such as:

1. Primary and secondary porosity and permeability characteristics of the materials, based on experience with these or similar materials.
2. Aquifer boundaries.
3. Estimated depth to water table; saturated thickness, estimated from width of outcrop area.
4. Relationship between topography and hydrology; recharge and discharge areas.
5. Relationship between ground and surface waters.
6. Estimated well yield, based on previous experience with a similar aquifer.
7. Ground-water quality; fresh or saline.

The results of this interpretation are a hydrologic model of aquifer limits, ground-water occurrence, aquifer operation, and ground-water quality. Other exploration techniques, such as test drilling or electrical resistivity surveys, may then be used to confirm this model or to indicate the need for changes.

In the operational use of remote sensing for ground-water exploration, it is desirable to simplify and minimize data processing, analysis, and interpretation procedures, unless detailed procedures prove necessary because of complex local conditions. Experience has shown that an adequate ground-water interpretation can be made from a series of 5 to 8 image overlays (figs. 11 and 12). These overlays are maps that show: (1) location of landmarks, (2) drainage lines,

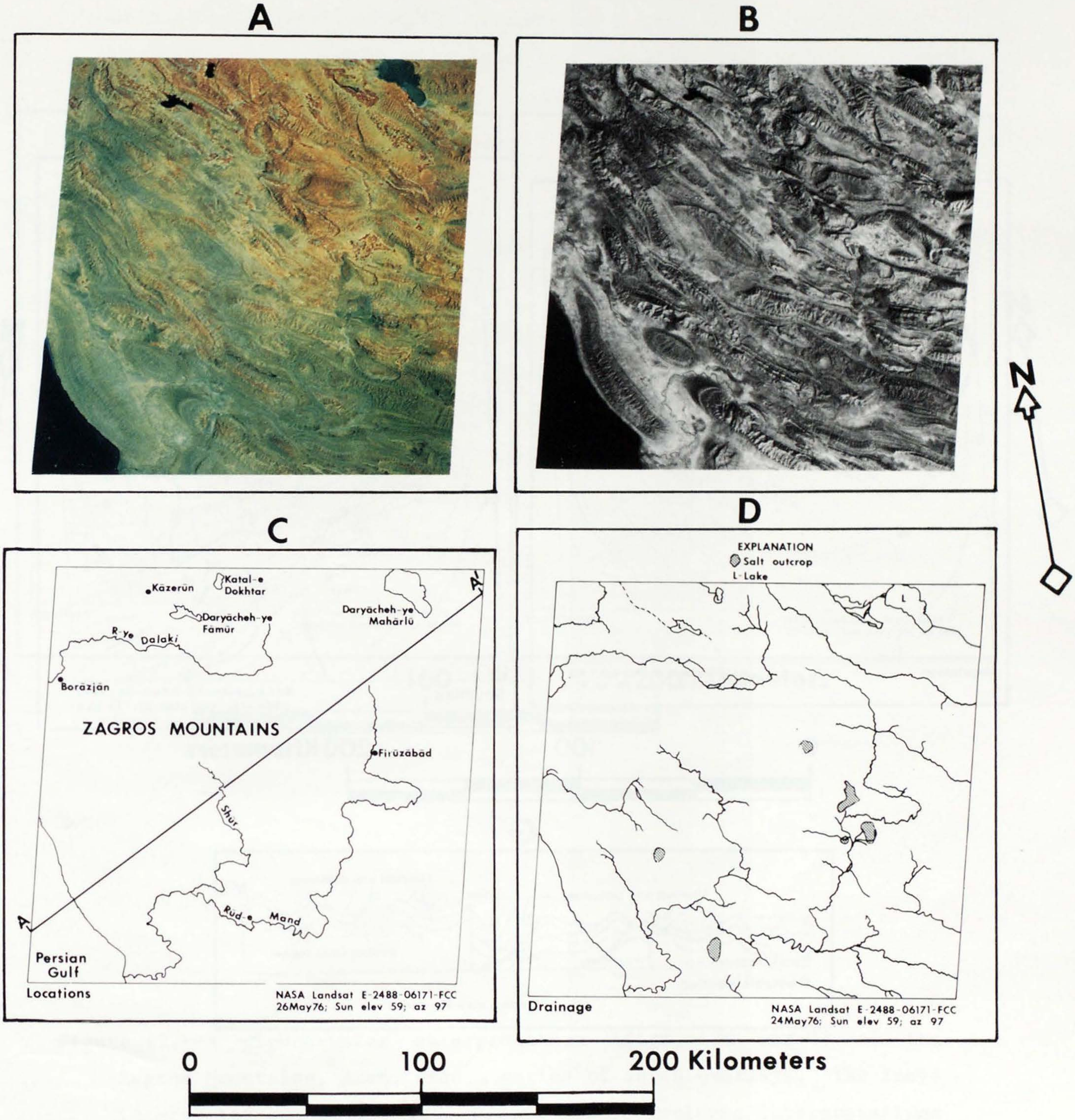
A
B
C
D
N
•Kāzerūn
Katal-e Dokhtar
Daryācheh-ye Fāmūr
R-ye Dalaki
Daryācheh-ye Mahārlū
Borāzjān
ZAGROS MOUNTAINS
Fīrūzābād
Shur
Rud-e Mand
A
A'
Persian Gulf
Locations
NASA Landsat E-2488-06171-FCC
26May76; Sun elev 59; az 97
EXPLANATION
Salt outcrop
L-Lake
L
Drainage
NASA Landsat E-2488-06171-FCC
24May76; Sun elev 59; az 97
0
100
200 Kilometers

Figure 12.--

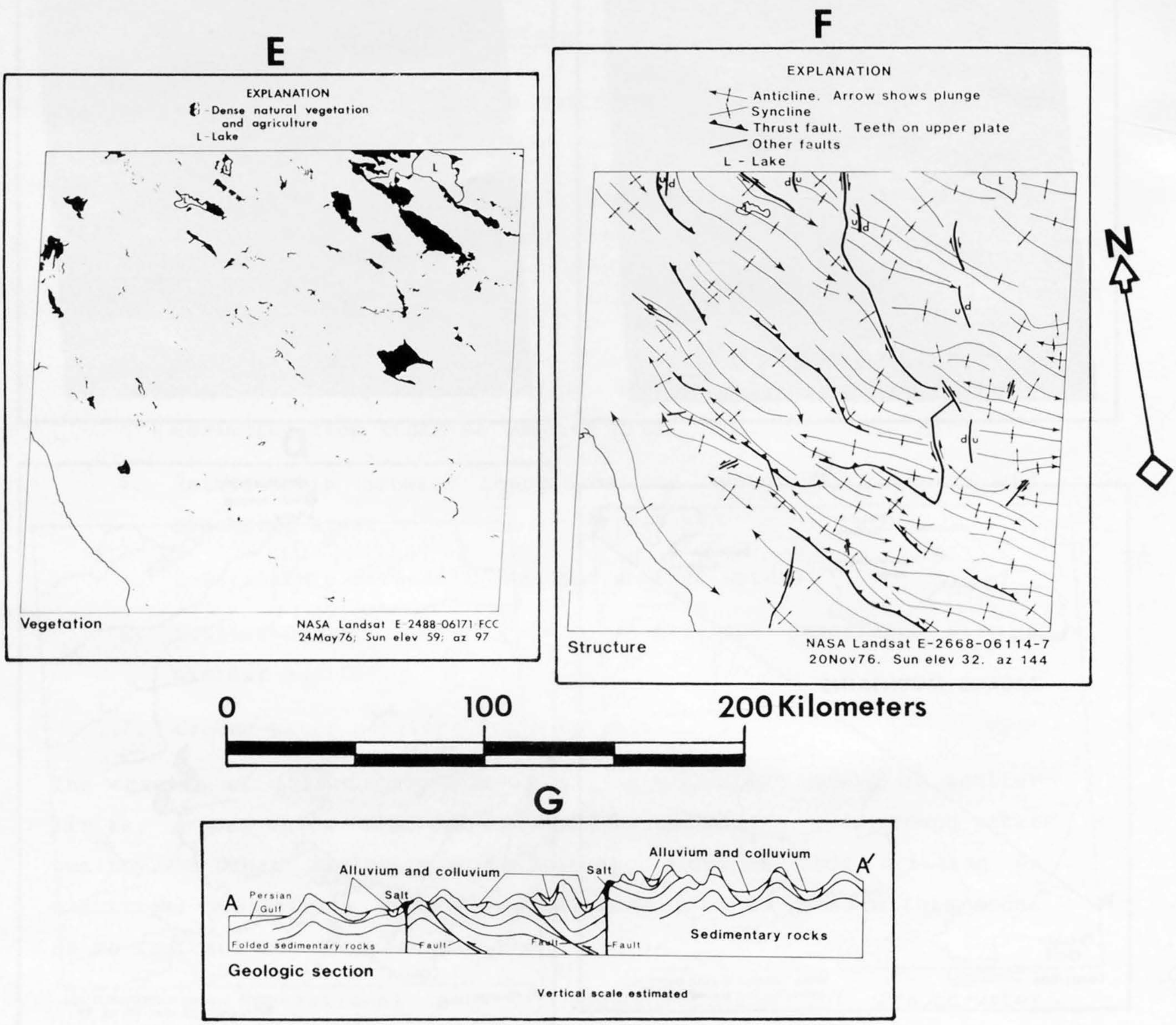
E
EXPLANATION
Dense natural vegetation and agriculture
L - Lake
L
Vegetation
NASA Landsat E-2488-06171-FCC
24May76; Sun elev 59; az 97
F
EXPLANATION
Anticline. Arrow shows plunge
Syncline
Thrust fault. Teeth on upper plate
Other faults
L - Lake
Structure
NASA Landsat E-2668-06114-7
20Nov76. Sun elev 32. az 144
N
0
100
200 Kilometers
G
A
Persian Gulf
Alluvium and colluvium
Salt
Alluvium and colluvium
Salt
A′
Folded sedimentary rocks
Fault
Fault
Fault
Sedimentary rocks
Geologic section
Vertical scale estimated

Figure 12.--

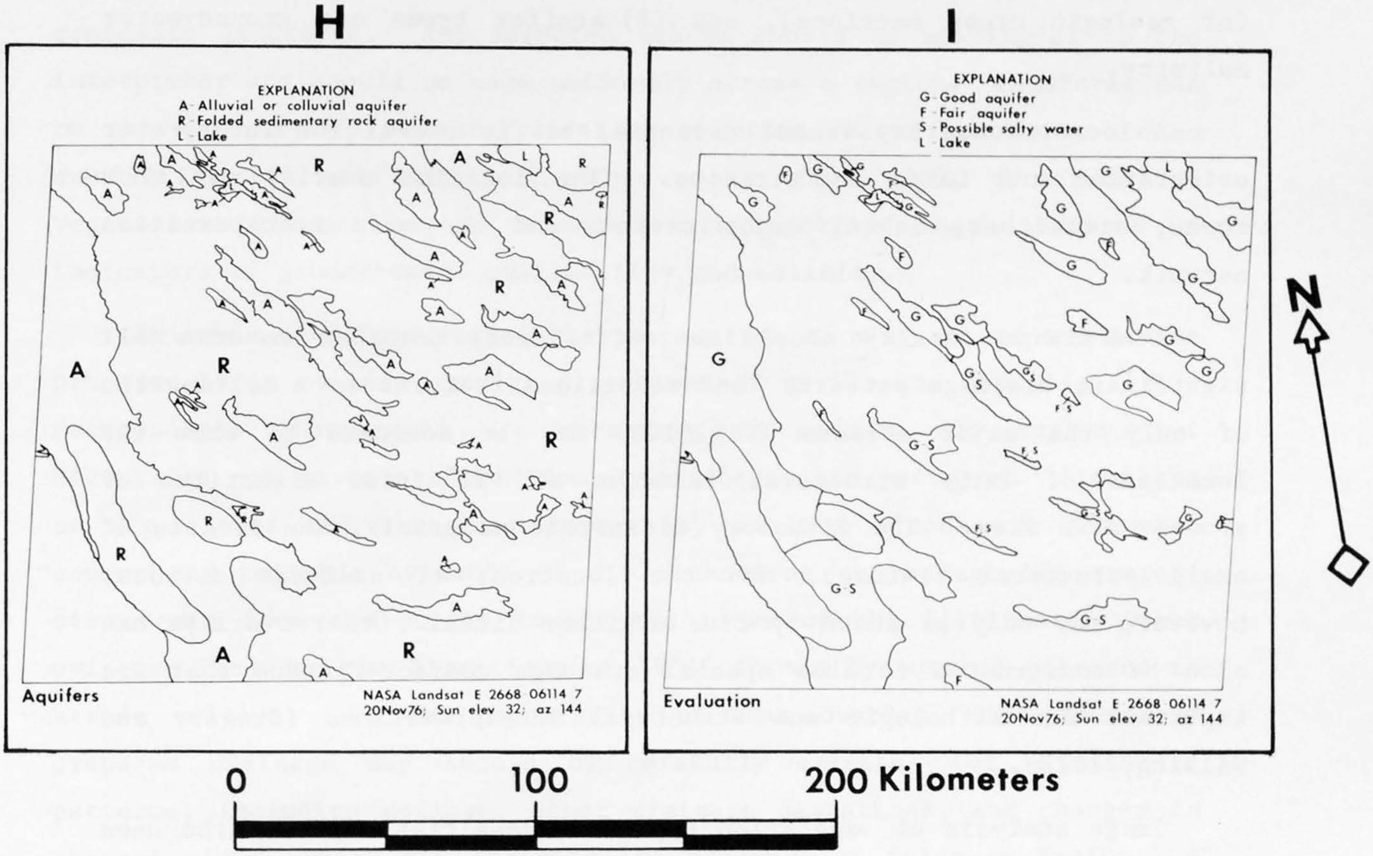

Figure 12.--A ground-water interpretation (figs. 12H and I) of the Zagros Mountains, Iran, used a series of seven overlays. The image interpretations (figs. 12C, D, and E) and geologic interpretations (figs. 12F and G) were made from NASA Landsat images E-2488-06171-FCC on May 24, 1976 (fig. 12A), and E-2668-06114-7 on November 20, 1976 (fig. 12B).

(3) natural vegetation and cropland, (4) landforms, (5) strike and dip symbols, (6) fold axes, faults, and lineaments; (7) surface lithologies (or geologic cross sections), and (8) aquifer types and ground-water salinity.

A location overlay is not essential but is useful for interpreter orientation and image registration. The location overlay may show towns, shorelines, lakes, major rivers, and the main transportation network.

A drainage overlay should be sufficiently detailed to show all significant drainage patterns and densities (textures). A delineation of only the major streams (fig. 12D) may be adequate to show the locations of large structural features and to infer directions of ground-water flow. The lithology of surface materials, the effects of small structural features, and the locations of drainage divides, however, may only be shown by fine drainage lines. Other overlays can also be constructed to show special drainage characteristics that are important for lithologic and structural interpretations (Gregory and Walling, 1973).

Image analysis of vegetation types and densities may show the need for an interpretive vegetation overlay, and may indicate the types of information that should be shown (figs. 11E and 12E). In arid regions, for example, the presence of dense natural vegetation may indicate locations of springs, seeps, and a shallow water table, or it may indicate only an increase of precipitation at higher elevations. The presence of cropland indicates nonsaline soils; irrigated crops in interstream areas generally indicate the availability of fresh ground water for irrigation pumpage. The absence of vegetation in an area that should have a shallow water table is indicative of salty ground water; this interpretation may be partly confirmed by the presence of salt crusts or very light toned soils.

A complete landform overlay is necessary for interpretations of surface lithology and ground-water occurrence. Landforms should be delineated and labeled carefully so that the overlay will be as useful as possible for these purposes. There is not general agreement on the delineations and labels that should be applied to many erosional and composite landforms. Any selected scheme should be meaningful to the interpreter and should be used uniformly across a region. Landforms can be the main key to an interpretation of ground-water occurrence in an area (fig. 11F and 11J). In other areas (fig. 12), structure and vegetation patterns may be somewhat more important than landforms as indicators of ground-water availability and salinity.

In areas of folded rocks, the preparation of a structure map may be preceded by an overlay showing directions of strike and dip (fig. 11G). Stereoscopic photographs are necessary to measure dip angles, but directions can be determined from image shapes and patterns. Flatirons on dip slopes and irregular topography on back slopes are the most common and reliable evidence of dip directions on Landsat MSS images: strata dip from the points toward the bases of the flatirons. Other evidence includes the directions of "V's" formed by outcrop patterns in stream valleys. In the preparation of this overlay, the previously prepared drainage map should be carefully examined for significant patterns, including doglegs, other drainage deviations, and changes in channel slope, which may indicate the presence of folds or faults. A strike and dip overlay is especially useful in terranes where sedimentary rocks are massively bedded (fig. 11), where small-scale topography has been rounded by erosion, and where folds have low relief or otherwise are somewhat obscure.

A geologic interpretation is considerably aided by preparation of a separate structure map. Fold types, axis positions, and directions of plunge are indicated by the strike and dip overlay (fig. 11G) or by image shapes and patterns (fig. 12B). Faults may be drawn wherever there is evidence for rock movement, such as displacements in outcrop pattern, topography, and drainage lines (fig. 12F). Triangular facets may be visible on both aerial photographs and Landsat MSS images (fig. 11H); these facets mark the general location and trend of fault or fault-line scarps.

Lineaments should be included on a structure overlay, because they may be presumed to be water conduits for purposes of a hydrologic interpretation. Carter (1976, p. 92-93) suggested a classification of lineaments in which reliability is indicated by colors or line intensity. Reliability classes may include (1) linear features confirmed by published maps; (2) those detected by two or more interpreters; (3) those detected by one interpreter, but believed to be mostly faults and other fractures; and (4) other linear features. Landform, drainage, and vegetation maps should be rechecked for linear patterns and trends at this stage of interpretation.

Compilation of a geologic map or cross section is necessary as a base for interpretation of ground-water occurrence. Cross sections (figs. 11I and 12G) are especially useful to the interpreter in formulating a three-dimensional conceptual view of the geology. Some lithologies are inferred by image shapes and patterns. Other rock types are best determined by a scientist with previous experience in photograph interpretation and previous knowledge of an area.

An aquifer overlay is necessary for a complete hydrologic interpretation. This map shows aquifer types, relative aquifer thicknesses, and areas of fresh or saline water (figs. 11J and 12I). It may also show major recharge areas, discharge areas, and directions of ground-water movement. An aquifer overlay is based upon the information that was developed in all previously constructed maps. Well yield and perennial water production from shallow aquifers are determined by aquifer type and material, areal extent, saturated thickness, position with respect to ground-water flow patterns, and amount of precipitation available for aquifer recharge.

The largest well yields and amounts of water production generally are available from thick, widespread, coarse-grained alluvial materials. Moderate amounts of water may be available from smaller areas, thicknesses, and sand sizes of unconsolidated rocks, including residual materials. Fractures in consolidated rocks may produce small to large amounts of water. More than one aquifer type may occur at shallow depths and thus may increase potential water production.

Depth to water table partly determines the saturated thickness of an aquifer. Relatively flat lowland areas have a shallow water table which may be only slightly higher than the water in streams and lakes. Broad and slightly dissected upland areas have a somewhat deeper water table. The deepest water table generally is found beneath steep slopes and narrow hills or ridges.

In arid regions, shallow aquifers may have only low yields of mineralized water unless there is adequate annual recharge to these aquifers from precipitation. Such recharge may be determined from remotely sensed images that show winter snowpack on mountains or a forest cover (indicating at least seasonal precipitation) at higher elevations. In all regions most aquifer recharge occurs on relatively flat areas and coarse-grained soils. Unusually large amounts of recharge may occur on shallow slopes near the bases of hills and mountains. The largest well yields are obtained near ground-water discharge points, lines, or areas, if everything else is equal. Natural ground-water discharge may occur at a spring, seep, stream, or lake. Discharge may also occur by transpiration from phreatophytes in areas with a shallow water table.

Shallow Sand and Gravel Aquifers

For the purposes of this report, aquifers are divided into two groups--shallow sand and gravel types and consolidated rock types. The sand and gravel aquifer group includes all coarse-grained, unconsolidated, water-bearing materials of fluvial, coastal, glacial, eolian, and residual origin. The mapping of sand and gravel aquifers depends upon the detection and recognition of landscape features that indicate the presence of these materials. Both aerial photographs and satellite images have proven to be well suited to this objective. All features in the interpretation checklist in table 3 have been detected on Landsat MSS images. Locally, other features may be important, and many smaller landscape features may be visible only on aerial photographs.

Table 3.--Checklist of features that indicate the occurrence of shallow sand and gravel aquifers on Landsat MSS images

Alluvial features:

1. Coarse drainage texture (arid region) or low drainage density (humid region).
2. Alluvial cone or fan; coalescing fans; bajada. Splay pattern representing partly formed or dissected fan. Dendritic, parallel, or fan drainage. Disappearance of drainage lines on image.
4. Broad and relatively flat-bottomed valley. Valley is wider than the meander belt.
5. Meander loop showing location of point bar. Meander scar or braided drainage scar in floodplain; oxbow lake.
6. Natural levee; levee complex.
7. Underfit or abandoned valley. Valley may contain ponded drainage or have a stream meander wavelength smaller than that of the floodplain and terraces.
8. Elongate lake or alined lakes and ponds, representing remnants of a former drainage network.

Coastal features:

1. Arc delta (coarsest material); composite and estuarine deltas.
2. Cheniers or beach ridges.
3. Fan-shaped area of different soil, vegetation type, or land use--indicating a landlocked arc delta.
4. Alined oblong areas of different soil, vegetation, or land use--indicating landlocked bar, spit, or beach. Drainage deviation or centripetal pattern at upstream boundary.

Glacial features:

1. Esker; valley train.
2. Outwash plain.
3. Splay soil tone or vegetation pattern, representing partly formed alluvial fan.
4. Other alluvial features (above).

Table 3.--Checklist of features that indicate the occurrence of shallow sand and gravel aquifers on Landsat MSS images -- Continued

Eolian features:

1. Longitudinal, transverse, parabolic, and star dunes. (Wind streaks, shown as parallel soil tone or vegetation pattern in image, generally indicate thin or fine-grained soil).

Residual features:

1. Smooth topographic surface that lacks bedrock outcrops. Low relief.
2. Coarse drainage texture. Dendritic pattern of small tributaries.
3. Light toned soil.
4. Wetlands at approximately the same elevation as nearby major streams.

Consolidated Rock Aquifers

Virtually all consolidated rocks contain some ground water at shallow depths, but the size of well yields depends on rock type, primary permeability (tubular permeability for basalt flows), amount and intensity of fracturing, and solubility. Aquifer productivity is also determined by topographic position and structure. A checklist can be used to determine differences in rock types on remotely sensed images, but previous knowledge or field study may be necessary to identify some lithologies. A checklist can also be used to identify fold and fracture patterns and locations. All features in table 4 have been seen on Landsat MSS images, but the lists are not intended to be all inclusive.

DATA SOURCES

At least some aerial photographs are available for nearly all of the United States; a few exceptions are small areas in Alaska. An index to recent photographs held by Federal agencies is available as a map titled "Status of aerial photography in the United States" from:

National Cartographic Information Center (NCIC)
U.S. Geological Survey
507 National Center
Reston, Virginia 22092

The NCIC is also the source for digital topographic data. The best sources for historical aerial photographs are U.S. Army Corps of Engineers District Offices in the eastern United States and various Federal and State agencies in the western States. A wide selection of aerial photographs is also held by commercial aerial survey companies.

Landsat images, Skylab photographs, and all aerial remotely sensed data acquired by U.S. National Aeronautics and Space Administration are available from:

User Services
EROS Data Center
Sioux Falls, South Dakota 57198

Table 4.-- Checklist of features that are important for mapping consolidated rock aquifers on Landsat MSS images

Rock type:

1. Landform; topographic relief; erosional characteristics.
2. Outcrop pattern--banded pattern for sedimentary rocks; lobate outline for basalt flows; arcuate or faulted boundaries for igneous intrusions.
3. Drainage pattern and drainage texture (density).
4. Fracture type and symmetry (as indicated by lineaments).
5. Topographic position; steepness of slope; presence or absence of erosional terraces on hillsides.
6. Shape of ridgeline and plateau edge.
7. Type and density of vegetation cover; land use.
8. Presence of sinkholes (visible only where occupied by water or distinctive vegetation).
9. Tone or hue; image texture.

Folds:

1. Ridge and valley topography; mountain, dome, and elliptical hill; short, parallel and intersecting ridge crests with V-shaped sections (complexly folded metamorphic rocks); cuesta or hogback.
2. Flatirons on dip slope and irregular topography on back slope; parallel to dendritic drainage on dip slope and angulate or trellis drainage on back slope; uniform distribution of vegetation on dip slope and vegetation banding parallel to ridge crests on back slope.
3. Banded outcrop pattern not related to topography. U-shaped to V-shaped map pattern of ridges.
4. Trellis, radial, annular, or centripetal drainage pattern; partly developed pattern of these types.
5. Major deflection in stream channel; change in meander wavelength or change from meandering to straight or braided channel.
6. Assymmetric drainage; channel not centered between drainage divides.

Table 4.-- <u>Checklist of features that are important for mapping consolidated rock aquifers on Landsat MSS images--Continued</u>

<u>Lineaments:</u>

1. Continuous and linear stream channel or valley; discontinuous but straight and alined valleys, draws, swags, and gaps.
2. Elongate or alined lakes, large sinkholes, and volcanoes.
3. Identical or opposite deflections (such as doglegs) in adjacent stream channels or valleys; alinement of nearby tributaries and tributary junctions.
4. Elongate or alined patterns of natural vegetation; thin strip of relatively open (may be right-of-way) or dense vegetation.
5. Alinement of dark or light soil tones.

The Data Center also holds U.S. Geological Survey mapping photographs and high-altitude panchromatic black-and-white and color-infrared photographs. Other sources of existing remotely sensed images and sources of new imagery missions are listed by May (1978, appendixes A-B).

Inquiries about the availabiity of aerial photographs for Canada should be made to:

National Air Photo Library
615 Booth Street
Ottawa, Ontario K1A 0E9
Canada

Landsat images acquired by Canadian receiving stations are available from:

User Assistance and Marketing Unit
Canadian Centre for Remote Sensing
717 Belfast Road
Ottawa, Ontario K1A 0Y7
Canada

The availability of aerial photographs elsewhere in the World is dependent upon national regulations and restrictions. Repetitive Landsat images are available for nearly all areas of the World; there are no restrictions on image distribution. Some Landsat scenes were tape recorded and may be ordered from the EROS Data Center. Other scenes are available only from national or regional distribution centers. European Landsat scenes may be ordered from:

European Space Agency
Earthnet User Services
Via Galileo Galilei
000 44 Frascati, Italy

Information on the availability of Landsat data from other non-U.S. receiving stations can be obtained from the EROS Data Center.

DATA SELECTION

One of the most important things that has been learned since repetitive satellite imagery has become available is that time of year is critical for obtaining maximum geologic and hydrologic information from the images. The exact best time depends on local conditions and weather patterns as well as interpretation objectives. The best range of dates for acquisition of Landsat for selected objectives in the United States is shown in table 5. Obviously, times other than those listed might be better in other parts of the World. Changes in Sun-elevation angle can be calculated from local latitude, but the best times to observe features such as soil moisture and vegetation differences depend upon local cycles of wet to dry, warm to cold, and bare soil to vegetation maturity. The best times for remotely sensed images must be determined from a knowledge of these local cycles and from experience in working with the images.

Time of year is somewhat less important for an interpretation of high-resolution stereoscopic aerial photographs than for satellite images. Nevertheless, bare soil conditions, some soil moisture conditions, and some vegetation contrasts may only occur for short periods of time. Local ground and vegetation conditions also determine some tones and patterns on radar images. Thermograms must be obtained at a carefully determined time when the desired temperature contrast occurs in an area.

A selection of digital or film data is based upon the perceived need for image enhancement or analysis and upon the methods available for these procedures (digital processing or photo-optical enhancement and visual analysis). Adequate ground-water interpretations have been made from standard product film images in many areas of the World. However, the selection of digital data ensure that problems do not occur with film latitude limitations, exposure time, and development time.

The selection of film transparencies or prints is partly a matter of personal preference and any plans for reproducing and viewing the images. Transparencies may be projected on a screen or viewed on a

Table 5.--Suggested periods for Landsat images in the United States of America

(Actual best time may vary because of local conditions or weather patterns)

1. Low Sun-elevation angle:
   a. Best: Nov. 20 - Jan. 20 (less than 25° at 35° N. latitude)
   b. Good: Nov. 1 - Feb. 15 (less than 30° at 35° N. latitude)
   c. Fair: Oct. 15 - Mar. 1 (less than 35° at 35° N. latitude)
2. Maximum area of bare soil:
   a. March - May (spring crops)
   b. Oct. - Dec. (winter crops)
3. Drainage patterns:
   a. Best: Nov. 20 - Jan. 20 (low Sun angle)
   b. Good: April - May (high stream stages)
4. Soil moisture patterns
   a. Best: April
   b. Good: March - May
5. Snowmelt patterns
   a. Best:March
   b. Good: Feb. - June
6. Native vegetation types and differences:
   a. Best: April - May, Oct.
7. Small lakes and ponds:
   a. Best: after heavy, intense showers
   b. Good: March - May after seasonally heavy rains
8. Native-vegetation density:
   a. Best: June - July (April - May for annual western grasses)
   b. Good: June - Sept.
9. Areas beneath deciduous overstory:
   a. Best: Dec. - March
10. Irrigated crops vs. dry-land farming:
    a. Best: dry period; crop grown enough to cover bare soil; crops of one type or several types with distinctive signatures (spectral reflectances)
11. Lithologies in glaciated terrane:
    a. Best: April - May
12. Desert vegetation:
    a. Best: April (at end of snowmelt season)
    b. Good: near end of unusually wet period

light table. Paper prints may also be viewed by transmitted light to avoid glare. The other consideration is that transparency film is a lower contrast material than print film. The selection of transparencies helps to ensure that all gray tones and colors in the original image are preserved. On the other hand, many satellite images have a low average contrast because of atmospheric haze. Increasing the contrast by selection of print film may aid image analysis and interpretation.

A final consideration in image selection is scale or enlargement factor. Small landscape features are easier to detect and identify on an enlarged image. The disadvantages of enlarged images are that (1) geometric distortions are introduced by enlarger lenses, (2) some image resolution is lost with each additional generation of film reproduction, and (3) a doubling of image scale quadruples the time required for delineation of landscape classes. A satisfactory solution to these problems consists of using a magnifying lens for analysis and interpretation of original-scale images. Another problem is that landscape features are easily detectable only when they are entirely within the interpreter's field of view or field of cognizance. Large, regional features are seen best on small-scale images.

IMAGE ENHANCEMENT

Image enhancement is seldom necessary. Most scientists use standard-product film images for ground-water interpretations (figs. 11 and 12, for example). Also, enhancement procedures never reveal landscape features that are completely obscure on the original images. The objectives of enhancement are to make analysis or interpretation faster and easier and to help ensure that significant landscape features are not overlooked. A variety of procedures are available for both photo-optical (Lockwood, 1975; and Ross, 1976, p. 170-212, for example) and digital (Sabins, 1978, p. 240-263; and Taranik, 1978, for example) image enhancement. All procedures have proven useful for special objectives or local landscape conditions. Fewer procedures (table 6) have general utility as an aid for ground-water interpretations.

Table 6.--Image enhancement procedures for ground-water interpretations

1. Enlarge image or areas of interest. Implemented by film enlargement or digital replication of pixels (picture elements) on display.
2. Level change--landscape features are easier to detect and identify if they are not very light or very dark. Change film exposure or shift ranges in digital value.
3. Generate color-composite image -- merge information from two or three separate images. Implement with color filters and film, color diazo materials, or color television display of digital data.
4. Contrast change -- increase or decrease contrast between landscape features and their surroundings. Complex and segmented contrast changes must be done by digital processing; film contrast may be increased by use of selected materials and by increasing development time.
5. Ratio images -- produced by dividing the digital values or film densities in one image by those in another image; generally used to enhance small differences in tone or hue of soils and rocks. A photo-optical method may be used for a simple ratio; digital processing is necessary for more complex algorithms.
6. Edge and spatial frequency enhancements -- enhance (or suppress) boundaries between features which have small differences in tone. A simple edge enhancement can be made by photo-optical processing, but digital algorithms generally produce better results.
7. Directional trend enhancement--used as an aid to lineament detection. Implemented by computer processing, generally box-type filtering by convolution. Equivalent results are obtained by viewing a film image through a Ronchi ruling (Pohn, 1970).
8. Edge segment extraction and line following -- an experimental digital approach to objective lineament mapping.
9. Principal components analysis -- statistical procedure for axes rotation of multiband images to produce uncorrelated data sets. Implemented by digital processing.
10. Stereoscopic image generation--the merging of digital image and topographic data to produce images for stereoscopic viewing.

IMAGE ORIENTATION AND STUDY

For orientation consistency, an image ordinarily is viewed with north at the top (away from the interpreter). For monoscopic viewing, however, the human eye may invert topographic relief, unless terrane shadows fall toward the interpreter. If the topography appears inverted, the image should be rotated 180°. A vertical view of an image is best for detection of most landscape features, but viewing at a low angle and slowly rotating the image may enhance lineaments. Viewing at a distance decreases resolution but also decreases the distraction of small cultural patterns; this procedure may help to detect large features or regional trends. Similarly, a projected image may be viewed close to the screen or at some distance, as well as in focus or out of focus.

Composite viewing has proven useful for image interpretation. The theory of composite viewing is that landscape features, which may not be apparent on a single image, will be obvious on a composite of two images obtained at different times (fig. 13). The images may be viewed together with a stereoscope or projected together on a screen (with a different colored filter for each image). For best results a color image and a black-and-white image should not be combined, nor should a snow covered scene be combined with a bare-ground scene.

DATA MERGING AND INTEGRATION

Remote sensing produces only some of the data that are used for ground-water studies. Other types include topographic, hydrologic, geologic, geophysical, and geochemical data. Because of the increasing complexity and intensity of ground-water studies, pertinent data sets are increasingly being digitized and compiled into hydrologic information systems. An information system is a multilayered, georeferenced [1] data base that can be used for exploration, inventory, evaluation, description, and prediction in an area. It consists of multiple, geographically registered data sets, associated files, and various data

[1] Georeferenced means that the spatial locations of points, lines, and areas in the data sets are identified and labeled.

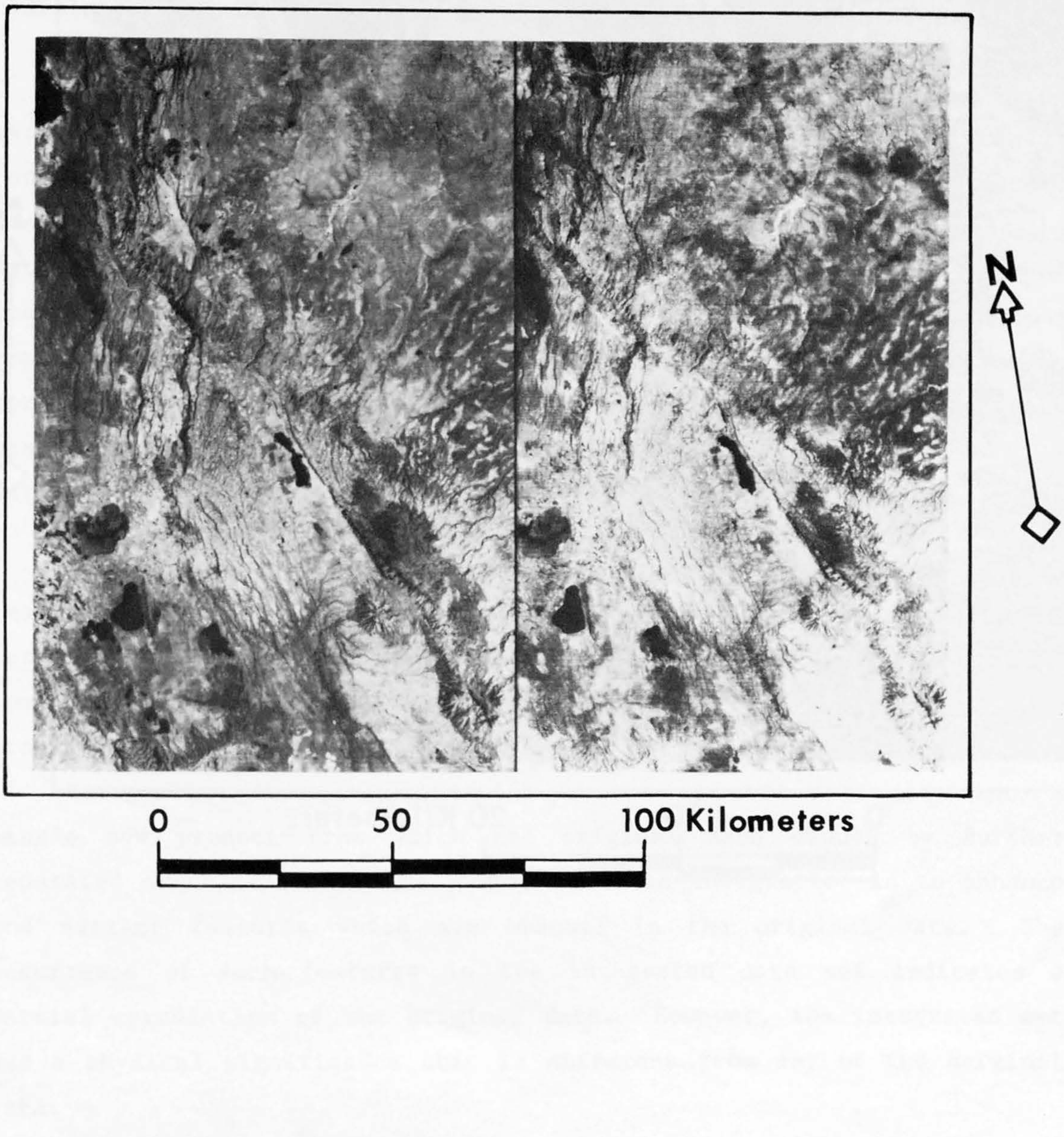

Figure 13.--More image detail can be seen by composite viewing (using a stereoscope) of two scenes acquired at different times. NASA near-infrared Landsat images E-2368-07031-7 (left) and E-1192-07174-7 show Nakuru, Kenya, and part of the East African rift zone on January 25, 1976 (left) and January 31, 1973.

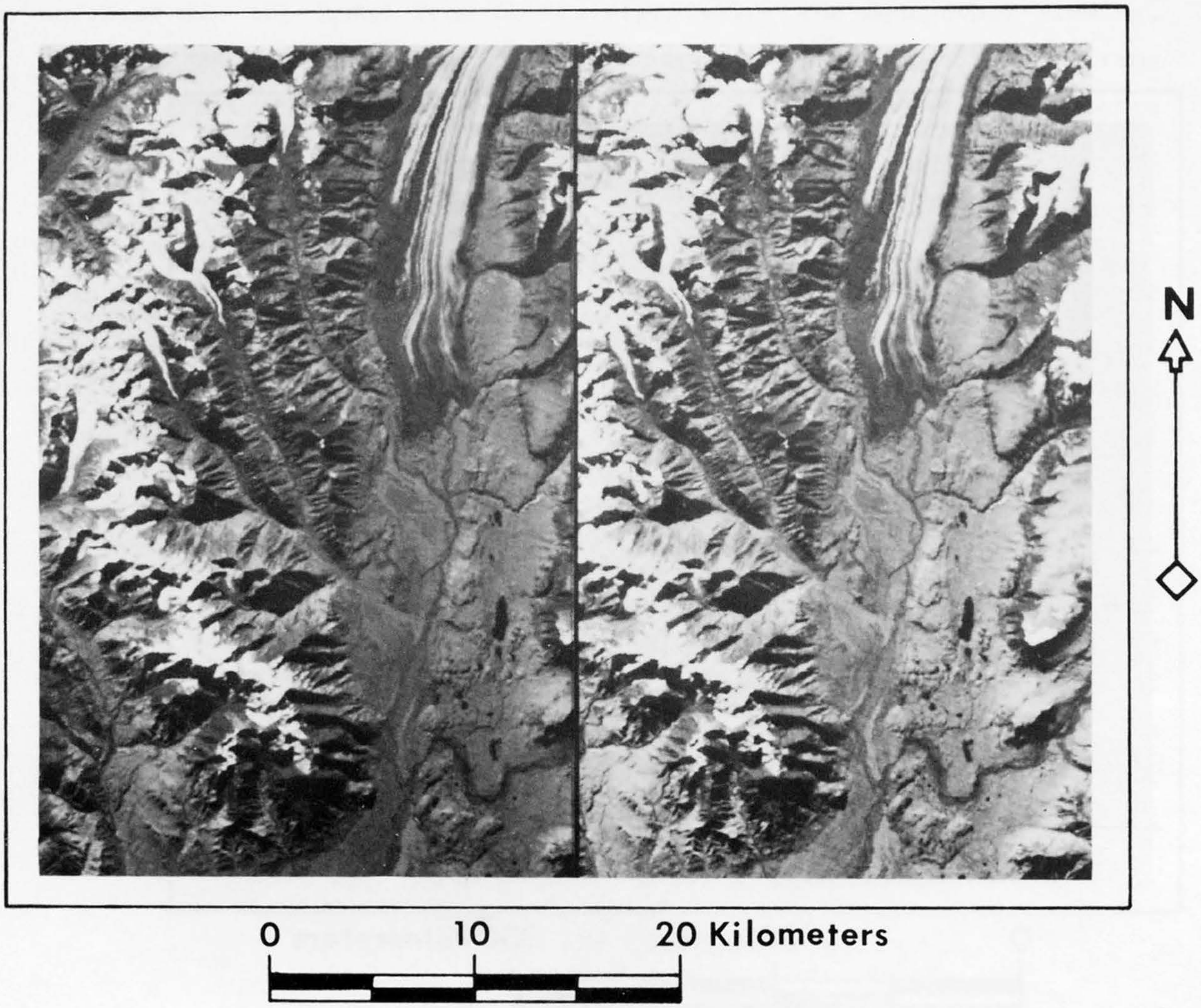

Figure 14.--Landforms and other landscape features near Orange Hill, Alaska, are shown on the Landsat near-infrared image base. Relief in the stereoscopic model is proportional to the magnitude of residual magnetic field intensity (stereoscopic pair). NASA Landsat image E-1422-20212-7 was obtained on September 18, 1973.

analysis functions. The maps and images in an information system show points, lines, areas, and surfaces (continuous or discontinuous). A remotely sensed image may be included in an information system for use as a base map. The information system may also include geologic and hydrologic data that have been obtained from an image by interpretation.

The extraction of information from diverse types of data may begin with digital merging and integration of selected data sets. Merging consists of combining two or more data sets into a composite product. The contribution of each original data set is apparent and can be extracted from the composite. Operations and intrinsic graphic options (table 7) include pattern, color, and stereoscopic composites. An example of data merging is the use of two data sets to generate images for stereoscopic viewing (fig. 14). One data set is used for the image base; the magnitude of the other data set is used for the measure of parallax or relief in the stereoscopic model.

The purpose of data merging is to compare positions and identify features, anomalies, and trends in the composite. The original data sets need not be correlated or physically related, but the occurrence of common features indicates a correlation of the original data in these areas.

Integration is the combination of two or more data sets into a single new product from which the original data cannot be further separated or calculated. The purpose of data integration is to enhance and extract features which are obscure in the original data. The occurrence of such features in the integrated data set indicates a partial correlation of the original data. However, the integrated set has a physical significance that is different from any of the original data.

Integration operations (table 7) include arithmetic combinations, classification, principal components transformation, and various logic functions and decision rules. An example of integration is a Bouguer gravity/magnetic intensity ratio, which may be displayed as an image (fig. 15). The graphics options for data integration include virtually all types of plots, maps, and images.

Table 7.--Processing and display options for data merging and integration

Merging operations and graphics

1. Patterned map or combined map and image.
2. Color-composite map or image.
3. Stereoscopic map or image.

Integration operations

1. Addition, subtraction, multiplication, or division.
2. Maximum or minimum--highest or lowest values in two or more data sets.
3. Binary logic functions: $<$, $>$, $=$, AND, OR, TRUE, and FALSE--used to areally stratify levels and ranges in multiple data sets.
4. Principal components transformation -- creates uncorrelated data sets from original, partly correlated data.
5. Albedo calculation or color space transformation -- for multispectral, remotely sensed data; reduces the number of data sets.
6. Multiband classification: parallelepiped, minimum distance, maximum likelihood, or other algorithm -- for multispectral, remotely sensed data; extracts similar areas from the data sets.
7. Multiset classification-- class assignments result from multiple decision rules for spectral and spatial measurements in grid cell neighborhoods.

Integration graphics

1. Histogram of occurrence; cumulative histogram.
2. Section.
3. Contours.
4. Line or polygon map.
5. Image.
6. Shaded relief map.
7. Isometric projection or linear perspective.
8. Scatter plot or cluster plot.
9. Regression line.

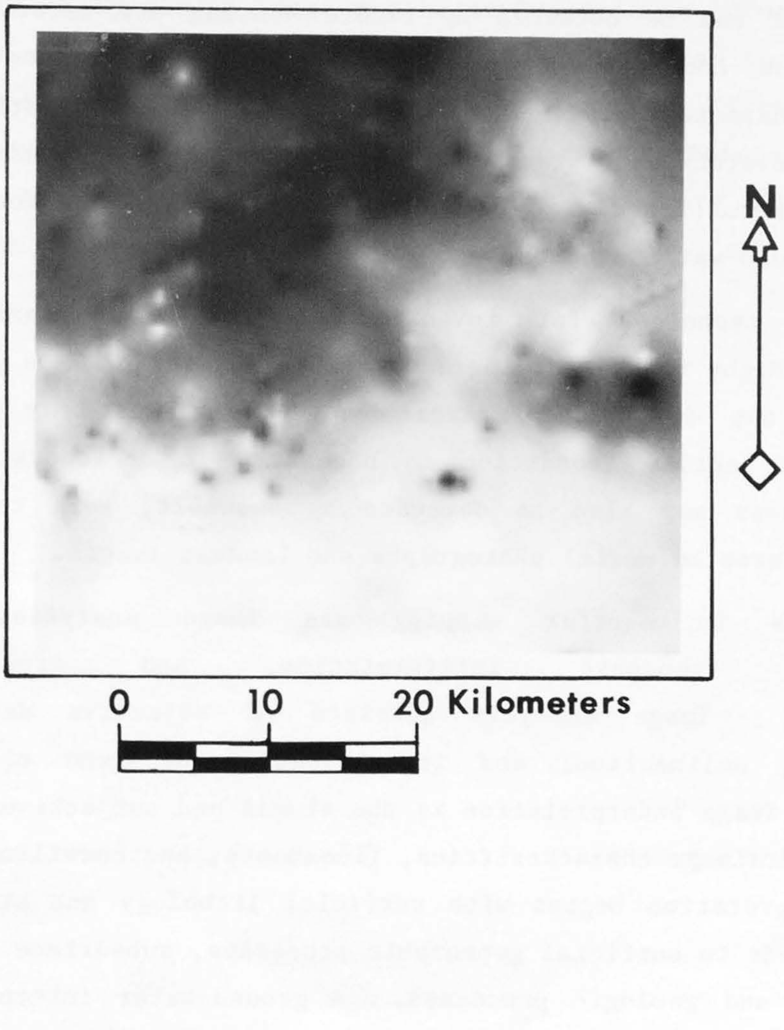

Figure 15.--Light image tones represent relatively high values of the Bouguer gravity/residual magnetic field intensity ratio near Orange Hill, Alaska. This image represents a simple form of data integration.

SUMMARY

Remote sensing can be used to inventory springs and seeps and to interpret lithology, structure, and ground-water occurrence. These interpretations are based on landforms, drainage patterns, land use, soil tones, and vegetation types and patterns. Limits to the information that can be obtained by remote sensing are determined by data acquisition conditions, sensor characteristics, surface cover, near-surface characteristics, and the need for interpretation and inference. Nevertheless, remote sensing can produce considerable ground-water information in many areas and should reduce the total time and cost of ground-water studies.

The best technique for inventory of seeps and springs is thermography. Night flights during unusually cold weather have produced best results, but day flights beneath a high overcast may also be acceptable. A leafless condition is necessary in deciduous forest. Springs and seeps may also be detected by snowmelt, soil tone, and vegetation patterns on aerial photographs and Landsat images.

The steps in aquifer mapping are image analysis, image interpretation, geologic interpretation, and ground-water interpretation. Image analysis consists of objective detection, classification, delineation, and identification of land cover and physiography. Image interpretation is the visual and subjective mapping of landforms, drainage characteristics, lineaments, and curvilinears. A geologic interpretation begins with surficial lithology and structure, and then proceeds to surficial geomorphic processes, subsurface geologic relationships, and geologic processes. A ground-water interpretation builds on the conceptual geology by inferring aquifer characteristics and water quality.

There are various sources for aerial photographs and satellite images. The selection process is very important for obtaining maximum geologic and hydrologic information from these data. Image enhancement is seldom necessary but helps to ensure that significant landscape features are not overlooked. Various enhancement procedures can be

implemented by photo-optical or digital processing. Composite viewing of images obtained at different times has proven useful for image interpretation.

A hydrologic information system is a data base that can be used for inventory, update, exploration, problem solving, and prediction in an area. A remotely sensed image may be included in an information system for use as a base map. The information system may also include geologic and hydrologic data that have been obtained from images by interpretation. Various merging and integration techniques may be used to obtain information from the diverse types of data in a hydrologic information system.

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