Airborne Remote Sensing for Geology and the Environment—Present and Future

U.S. Geological Survey Bulletin 1926

Cover: Past and present U.S. Geological Survey aircraft used for geophysical surveys are depicted flying over terrain typical of the foothills west of Denver, Colo. The aircraft, in order of age (left to right), are Beechcraft Model 17, Staggerwing; Douglas DC–3; Convair CV–240; and Fairchild Porter PC 6/C–H2.

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Airborne Remote Sensing for Geology and the Environment—Present and Future

Ken Watson *and* Daniel H. Knepper, *Editors*

U.S. GEOLOGICAL SURVEY BULLETIN 1926

A workshop report on the rationale for airborne remote sensing in earth science in the next decade

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1994

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Robert M. Hirsch, Acting Director

For sale by U.S. Geological Survey, Map Distribution
Box 25286, MS 306, Federal Center
Denver, CO 80225

Library of Congress Cataloging-in-Publication Data

Watson, Kenneth, 1935–
Airborne remote sensing for geology and the environment—present and future / Ken Watson and Daniel H. Knepper.
p. cm. — (U.S. Geological Survey bulletin ; 1926)
Includes bibliographical references.
1. Earth sciences—Remote sensing. 2. Environmental geology—Remote sensing.
I. Knepper, Daniel H. II. Title. III. Series.
QE75.B9 no. 1926
[QE33.2.R4]
557.3 s—dc20
[550'.28]

93–30781
CIP

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EXECUTIVE SUMMARY

In 1988, a group of leading experts from government, academia, and industry attended a workshop on airborne remote sensing sponsored by the U.S. Geological Survey (USGS) and hosted by the Branch of Geophysics. The purpose of the workshop was to examine the scientific rationale for airborne remote sensing in support of government earth science in the next decade. This report has arranged the six resulting working-group reports under two main headings: (1) Geologic Remote Sensing, for the reports on geologic mapping, mineral resources, and fossil fuels and geothermal resources; and (2) Environmental Remote Sensing, for the reports on environmental geology, geologic hazards, and water resources. The intent of the workshop was to provide an evaluation of demonstrated capabilities, their direct extensions, and possible future applications, and this was the organizational format used for the geologic remote sensing reports. The working groups in environmental remote sensing chose to present their reports in a somewhat modified version of this format. A final section examines future advances and limitations in the field.

There is a large, complex, and often bewildering array of remote sensing data available. Early remote sensing studies were based on data collected from airborne platforms. Much of that technology was later extended to satellites. The original 80-m-resolution Landsat Multispectral Scanner System (MSS) has now been largely superseded by the 30-m-resolution Thematic Mapper (TM) system that has additional spectral channels. The French satellite SPOT provides higher spatial resolution for channels equivalent to MSS. Low-resolution (1 km) data are available from the National Oceanographic and Atmospheric Administration's AVHRR system, which acquires reflectance and day and night thermal data daily. Several experimental satellites have acquired limited data, and there are extensive plans for future satellites including those of Japan (JERS), Europe (ESA), Canada (Radarsat), and the United States (EOS).

There are currently two national airborne remote sensing programs (photography, radar) with data archived at the USGS' EROS Data Center. Airborne broadband multispectral data (comparable to Landsat MSS and TM but involving several more channels) for limited geographic areas also are available for digital processing and analysis. Narrow-band imaging spectrometer data are available for some NASA experiment sites and can be acquired for other locations commercially.

Remote sensing data and derivative images, because of the uniform spatial coverage, availability at different resolutions, and digital format, are becoming important data sets for geographic information system (GIS) analyses. Examples range from overlaying digitized geologic maps on remote sensing images and draping these over topography, to maps of mineral distribution and inferred abundance.

A large variety of remote sensing data sets are available, with costs ranging from a few dollars per square mile for satellite digital data to a few hundred dollars per square mile for airborne imaging spectrometry. Computer processing and analysis costs routinely surpass these expenses because of the equipment and expertise necessary for information extraction and interpretation. Effective use requires both an understanding of the current methodology and an appreciation of the most cost-effective solution.

GEOLOGIC REMOTE SENSING

Geologic Mapping

There is a long historical background in the use of aerial photography for geologic studies. More recently, digital data from the TM satellite system and equivalent airborne systems have been successfully used for distinguishing among geologic units based on spectral-reflectance characteristics. Broad families of minerals can be identified or distinguished based on the presence or absence of absorption features due to ferric and ferrous iron and the hydroxyl (OH) and carbonate (CO_3) radicals. High spectral and spatial resolution provided by airborne imaging spectrometer systems permits even more detailed lithologic and stratigraphic discrimination based on subtle changes in mineralogy. Midinfrared (thermal) data provide additional mineralogical information, notably for silicate and carbonate minerals, and expand the capability for delineating lithologic units. Where lithology controls vegetation, multispectral remote sensing data offer a means of preparing lithologic maps that might otherwise be difficult to achieve.

Computer-enhanced digital images provide an excellent means for mapping the distribution and geometrical patterns of lithologic units that commonly reveal the tectonic setting and local fold and fault structures. Side-looking airborne radar (SLAR) images have shown variations in fold geometry that are controlled by faults in the basement rocks. The analysis of linear structural elements mapped from remote sensing data is widespread as a reconnaissance tool for determining fracture patterns on a local, regional, and continental scale in advance of field investigations. Study of the morphology of the Earth's surface using remote sensing has demonstrated that these data provide an effective means of extracting subtle structural and geomorphic information.

Imaging spectrometers provide the potential for extending broadband lithologic discrimination to detailed lithologic identification based on mineral content: the distribution of the individual iron oxide and hydroxide minerals can be applied to geologic mapping in general and to hydrothermal-alteration zonation mapping in particular. Individual clay mineral species associated with weathered and altered rocks and specific shale units can be identified and mapped, and sedimentary strata composed of limestone, dolomite, and gypsum can be uniquely separated and identified, thus opening a new era in the application of remote sensing techniques to lithologic mapping. In the midinfrared, igneous rock-type discrimination can be made based on emissivity characteristics controlled by chemistry and molecular structure. Inferred future uses of remote sensing include mapping intrusive and extrusive facies in igneous terranes, contact and regional facies in metamorphic terranes, facies changes in sedimentary terranes, and subtle structural control in arid regions of the west.

Mineral Resources

The mapping of anomalous limonite concentrations using data from MSS satellite and airborne-equivalent systems has been widely used for finding hydrothermally altered rocks. Extensive fieldwork is normally needed to distinguish limonite due to oxidation of sulfide minerals from limonite resulting from weathering of mafic minerals. In densely vegetated areas, remotely derived species composition and density variation data can be used as indirect means of mapping lithologic differences. Examples include association of coniferous trees with arenaceous rocks, low vegetation density on ultramafic areas, lower density of sagebrush on argillized volcanic rocks than on unaltered rocks and, in altered areas, anomalous growth of Ponderosa pine trees together with very low sagebrush density.

TM satellite (and the airborne equivalent called TMS, for Thematic Mapper Simulator) data are sensitive to clays and other OH-bearing minerals. Examples of mapping applications of these data include the argillized and opalized rocks of the Cuprite district, Nevada, that contain the detectable minerals kaolinite and alunite, and the limonitic hydrothermally altered rocks of the Goldfield mining district, Nevada, that also contain OH-bearing alteration minerals. However, mineral identification other than for limonite and the OH, HOH, and CO_3 minerals is not feasible with these data because of their broad spectral width. Consequently, separation of hydrothermally altered rocks from unaltered carbonate rocks, shales, and other rocks bearing minerals that have absorption features near 2.2 μm and 2.35 μm is not possible, nor is it possible to uniquely identify altered rocks that are primarily silicified. TM images have also been used for detecting spectrally anomalous soil derived from potassic altered rocks and for mapping vegetation anomalies in densely vegetated areas at a district scale.

Linear structures are routinely mapped from multispectral images to help characterize structural setting. In addition, radar data have been found useful for identifying topographically expressed fractures, and thermal data aid in finding fracture zones that concentrate moisture in the soil.

Current research, largely focused on high-spectral-resolution reflection and moderate-resolution emission data, indicates that by coupling data from imaging spectrometers with multispectral thermal-infrared scanners, it is possible to detect small but significant amounts of buddingtonite, pyrophyllite, and bastnaesite and to determine spatial variations relevant to the mapping of formative conditions of mineral deposits.

Future capabilities of remote sensing in mineral resource studies must involve detailed processing and analysis of imaging spectrometer and multispectral thermal data and the interpretation of these data in the context of mineralizing systems. Additional capabilities should include identification of the associations of plant communities with lithologies that are important for exploration, a more complete understanding of the nature and detection of metal-stressed vegetation, establishing subsurface continuity of regional-scale lineaments with geophysical data, and recognizing the relationship of local linear features to specific geologic structures that may have been formed during mineral deposition or that may have had some control on such deposits. Ongoing research on the spectral properties of minerals, rocks, and plants continues to reveal new uses of old data and the need to devise new analytical methods and types of data collection.

Fossil Fuels and Geothermal Resources

Multispectral scanner reflectance and thermal data from TM and TIMS (for Thermal Infrared Multispectral Scanner), primarily interpreted using photogeologic techniques, have been used to prepare detailed and reconnaissance geologic maps, particularly in poorly mapped or unmapped areas. SLAR has been used to map local and regional topographically expressed features that reflect geologic structures important to the accumulation of petroleum deposits. Specially processed images have been used to identify and map bleached zones that have been attributed to the seepage of hydrocarbons in sandstones and to map anomalous local occurrences or absences of ferric oxides. Various geobotanical effects have been observed, including a well-documented case caused by natural-gas seeps (local seepage of hydrocarbon gas that has affected both vegetation and soil conditions), and the detection of vegetation stress during late green-up or early senescence that may indirectly be indicative of the presence of hydrocarbons.

Identification of sedimentary facies affecting petroleum accumulations, possible carbonate accumulations associated with microseepage phenomena, direct identification of oil from ocean seeps using fluorescence detection, and the detection and mapping of regional fracture patterns that may indicate areas of increased fracture permeability are examples of remote sensing in the field of petroleum exploration.

Based partly on work in other areas, airborne remote sensing methods that can be applied to geothermal exploration include detection of epithermal minerals, mapping silicification and fractures, identifying ammonium-bearing minerals, discovering anomalous surface-heat fluxes, and recognizing thermal metamorphism.

Future directions could include developments based on the direct detection of methane and other hydrocarbon gases and use of digital topographic models derived from stereo terrain images for mapping subtle topographic expression that can indicate structural controls.

ENVIRONMENTAL REMOTE SENSING

Environmental Geology

An ideal environmental remote sensing system requires high spatial resolution, high sensitivity to changes in baseline characteristics, proven and accessible technologies, and low cost. Airborne photography, which is familiar and relatively inexpensive, is ubiquitous in environmental studies despite obvious limitations—awkward archiving, lack of spectral resolution and sensitivity, and difficult integration with correlative GIS data and digital technologies. Photography is gradually being replaced by digital image data.

Pollution

Both satellite and airborne multispectral scanning systems have been used to map a variety of water-quality parameters in surface-water systems (chlorophyll concentrations, Secchi depth, total suspended solids, total phosphorus, dissolved organic carbon, turbidity, salinity/conductivity, and others). Airborne scanners provide a synoptic view that permits analyses of land cover and watersheds for recognizing local hazards such as nonpoint pollution, landfills, and unwise land use. Airborne laser fluorosensor systems are increasingly used to measure water quality. Airborne profiling systems are highly sensitive to airborne particulates, yielding the vertical as well as the horizontal distribution of air-quality pollutants. Imaging spectrometers and fluorosensors can be far more effective than photography for identifying water or soil pollutants.

Vegetation Inventory

Remote sensing, which has long been used to inventory and monitor vegetation, is now evolving toward the automated identification of specific species. It is currently limited to higher levels of classification (for example, certain hardwoods versus conifers, or certain classes of crops). Present-day airborne multispectral scanning techniques can be used to recognize extreme plant stresses that eventually result in plant death, and to yield a "greenness index," which is empirically correlated to biomass.

Ecotone Modification

Airborne remote sensing is used to monitor temporal changes in the transition zones between ecologic communities. Current capabilities typically center on the efforts of skilled interpreters employing photointerpretive techniques and multiband-image classification algorithms.

Fish and Wildlife Management

The distribution, depth, clarity, and trophic level of waters are being determined by airborne multispectral techniques. Thermal scanners have been used in arid environments to detect small seeps or springs, and longer wavelength radar has been used to detect standing water under forest canopies.

Fire Management

Satellite data (MSS, TM, and AVHRR) are used operationally to classify and map potential fire fuel in large areas in the Western United States, Alaska, and Canada. Airborne thermal scanners are used to detect fire hot spots and to map fire location at night or through smoke and haze. Future fire detection and mapping systems for the contiguous United States will be airborne rather than spaceborne because of the need for special sensors and for immediate and repeated coverage.

Global Climate

Satellite remote sensing permits global descriptions of the Earth at time scales as short as days or hours. Airborne remote sensing is important for calibrating satellite techniques, for permitting intense coverage, and for providing test platforms for sensor and technique development. The distribution and state of water is most readily mapped with microwave and thermal-infrared techniques. Vegetation maps are probably useful for detecting boundary migration. Sea-ice distribution and thickness mapping, relative soil-moisture mapping, and ice-sheet depth and structure profiling can be done using a variety of remote sensing techniques.

Hazards

Airborne remote sensing methods, because of their rapid deployment, synoptic view, and high spatial resolution (1–2 m), have potential for delineating and monitoring phenomena essential for the evaluation of many geologic hazards. Surface features such as scarps, hummocky terrain, scarred valleys, advancing flow fronts, lineaments, and vegetation distribution can readily be identified on aerial photographs. Low-sun-angle photos show subtle topography.

Landslides

Airborne multispectral surveys can be conducted to detect vegetation differences and to delineate clayey sediments or other ductile materials. Thermal-scanner surveys can detect patterns in near-surface ice and snow, lithologic boundaries, and water seepage along bedding planes. Multifrequency radar can be used to discriminate changes in surface roughness and moisture differences that may relate to ground stability.

Flooding

Under conditions of continuous cloud cover, radar can be used to acquire data to assess the extent of flooding. Under clear atmospheric conditions, photography provides an inexpensive means of mapping the land-water interface and monitoring changes.

Volcanic Hazards

The synoptic views provided by remote sensing data can have an important role in detecting the extent and progress of volcanic eruptions. Thermal-infrared surveys have mapped the extent of hot material, detected changes at night, and detected "hot spots" (usually fissures) from which hot gases are emitted. Remote sensing also provides useful information about lithology and structure in volcanic hazard areas. Differences among flow units and pre-eruptive conditions such as ground-tilting and swelling could be monitored by laser profiling.

Faults and Earthquakes

Radar measurements can detect changes in elevation, roughness, and moisture content of soils in fault zones. Both radar and thermal-infrared scanners are extremely sensitive to the moisture content of the soil, which can indicate differences in soil type across fault boundaries. Three-dimensional, high-resolution digital terrain maps, digital radar, multispectral scanners (reflectance and thermal), and laser profilers have the potential to provide valuable topographic, structural, and lithologic information for identifying faults and for monitoring changes associated with them.

Coal Fires

Because coal fires create conditions where the ground is recognizably warmer, airborne thermal scanners have been used to monitor and in some instances identify these conditions. Multispectral scanners could also be used to detect stressed or dead vegetation resulting from the high heat flow and associated gases.

In-Mine Ground-Control Hazards and Subsidence

Fracturing in the rock mass within mines, and mining areas prone to this hazard, can often be identified through lineament analysis. Geomorphic aspects and vegetation differences that may be associated with fracture-controlled porosity or subsidence can be detected. Subtle soil-moisture differences and surface-roughness characteristics, which might provide indications of fracture controls or possible subsidence, could be measured from thermal and radar data.

Precursors

Because radar and thermal-infrared data can be used to detect moisture and surface-elevation changes, it would be worthwhile to evaluate their use for detecting precursor conditions for various hazards including landslides and subsidence.

Water Resources

Visible- and near-infrared-wavelength photography and images are used to provide direct observation of a water body (including extent of snow and ice, ice concentration, turbidity, and floodplain mapping), whereas data beyond the photographic limit (0.9 μm) are used to interpret surface features associated with subsurface water (surficial geologic and geomorphologic features and vegetation, and indicators of evapotranspiration).

Snow and Ice

Estimation of meltwater quantity requires information both on the areal extent of snow cover, which can be accomplished using photos and images, and on the snow's water equivalent. Gamma-ray profiles are the most accurate for the latter but they are flown at low altitude and thus have a narrow footprint. Microwave data can also be used to infer snow extent, onset of snowmelt, and snow water equivalent. An experimental four-frequency microwave technique offers the surveying advantage of a much broader footprint than the gamma-ray technique.

Soil Moisture

Thermal-infrared scanning is used to examine areas of ground-water discharge and diffuse shoreline seepage. Infrared photography is used to distinguish phreatophytes. Linear features can be mapped on images and photographs to locate wells with enhanced yields. Both thermal-infrared and microwave techniques can be used for characterizing soil-moisture conditions in the uppermost 5 cm, but they cannot be applied in forest-covered areas.

Evapotranspiration

Thermal-infrared and microwave techniques can be used to provide an indirect estimate of evapotranspiration; however, their accuracy depends on how well the different soil types have been mapped and their soil characteristics determined. Estimates are limited to cultivated areas, prairies, and savannas.

FUTURE RESEARCH

Research topics identified during the workshop were organized in three categories: (1) likely research advances focused on current trends and developments, (2) research needed to define the likelihood of success, which identifies critical areas that need more attention, and (3) current barriers to future research, which reflects some concerns and needs of remote sensing professionals.

The field is changing rapidly as a result of significant instrument and computer developments and because of enhanced analysis and interpretation capabilities. However, old problem areas remain, including lack of understanding of how lineaments relate to tectonic environments, and the causes and detection of stressed vegetation. Technological developments have also introduced a number of data-related issues such as volume, formats, availability, and the increased expertise required to analyze and interpret modern remote sensing data.

AIRBORNE REMOTE SENSING FOR GEOLOGY AND THE ENVIRONMENT—PRESENT AND FUTURE

Ken Watson *and* Daniel H. Knepper, *Editors*

INTRODUCTION

Ken Watson, *Workshop Chairman*

During the period January 26–29, 1988, a group of leading experts from government, academia, and industry attended a workshop on airborne remote sensing sponsored by the U.S. Geological Survey (USGS) and hosted by the Survey's Branch of Geophysics. The purpose of the workshop was to examine the scientific rationale for airborne remote sensing in support of government earth science in the 1990's.

This document developed as a result of these discussions and is intended to provide our best evaluation of the demonstrated current capabilities of remote sensing, their direct extensions, and possible future applications in geologic and environmental earth science. It reflects the state-of-knowledge at the time of the workshop and does not attempt to update technological developments that have occurred in plans for satellite launches or changes in the commercial availability of instruments. As such, it provides a useful yardstick to project current advances into the remainder of the decade. The report is primarily for managers and emphasizes the use of airborne remote sensing to solve problems. In order to make the document as functional as possible, we have not attempted to provide a comprehensive scientific text nor a detailed discussion of the methods. Readers interested in additional details and further background are encouraged to consult appropriate review articles in the general scientific literature, such as Goetz and others (1983), Goetz, Wellman, and Barnes (1985), and Watson (1985), and recent symposium volumes and the proceedings of various thematic conferences on geologic remote sensing conducted and run by the Environmental Research Institute of Michigan. USGS members of this workshop (see appendix) can be consulted for further guidance.

This is an informal presentation intended to stimulate interest in the substantial benefits of remote sensing methods to future earth-science programs. We hope that its reading will lead to a dialogue between scientists and managers on the appropriate ways to employ these tools in their mission objectives. It should become apparent during the reading of this document that remote sensing has evolved considerably from a simple exercise in the use of familiar and easily understood photographic techniques into a sophisticated field requiring technical expertise.

AVAILABLE REMOTE SENSING DATA

SATELLITE DATA

There is a large, complex, and often bewildering array of remote sensing data available. Probably the most familiar are the 80-m-resolution Landsat Multispectral Scanner System (MSS) images in four reflectance channels (green, red, and two near-infrared) available on film and computer-compatible tapes for processing, creating composites, and display. That system has now been largely superseded by the Thematic Mapper (TM) system, which acquires 30-m-resolution data in six reflectance channels (three in the visible range and three in the near-infrared) and 120-m-resolution thermal data in a single channel. These data are available worldwide from EOSAT, a private company to whom the Landsat system was transferred in 1985. Many United States scenes are already in the USGS' Branch of Geophysics tape library, and others that are in the FOLD (Federally Owned Landsat Data) system can be obtained for the cost of duplication. Another commercial satellite is the French SPOT, with three spectral channels (roughly comparable to MSS) at 20 m resolution and an additional 10 m broadband reflectance (panchromatic) channel that can acquire image data at off-nadir angles (±27 degrees) for stereo viewing. The third major digital data set is from the National Oceanographic and Atmospheric Administration's AVHRR system, which acquires low-resolution (1 km) data twice daily in two reflectance and two thermal channels (a fifth channel is largely for atmospheric studies). The data are available through the National Space Data Archive.

Several experimental satellites have acquired limited data over the United States and other nations, and the

Table 1. Remote sensing data collection systems.

Status	Spectral region	System
Satellite systems		
Operational	Visible and near-infrared reflectance	Landsat MSS, TM
		SPOT
		AVHRR
	Thermal	Landsat TM (day)
		AVHRR
Experimental	Thermal	HCMM (day, night)
		Landsat TM (night)
	Radar	Seasat
		SIR–A, SIR–B
	Photography	Soyuzkarta
Future	Reflectance, thermal	JERS
		MODIS–EOS
	Imaging spectroscopy	HIRIS–EOS
	Radar	Radarsat
		SAR–EOS
Airborne systems		
Programmatic	Photography	NHAP/NAPP
	Radar	SLAR
	Dual-frequency radar profiler	LIDAR
Experimental	Imaging spectroscopy	AIS, AVIRIS
	Multispectral reflectance	TMS
	Multispectral thermal	TIMS
	Multifrequency laser	UV–DIAL
Commercial	Imaging spectroscopy	GERIS
	Multispectral thermal	Geoscan, Daedalus
	Reflectance, thermal	Daedalus (TMS)

availability of these data could be worth investigating for particular studies. Examples include radar (Seasat; SIR–A, SIR–B) and 500-m-resolution day and night thermal data (HCMM). The USGS has a modest inventory of the HCMM data.

Extensive plans for future satellites include those of Japan (JERS), Europe (ESA), Canada (Radarsat), and the United States (EOS). Strategies to employ remote sensing satellite images will need to consider these future developments. Table 1 provides a brief overview of some of the more common systems for those not familiar with the terminology. The terms operational and programmatic mean that data are routinely acquired and coverage is available over all or most of the United States. Experimental data sets are of limited availability and limited geographic and seasonal coverage. Commercial systems are those that can be contracted to acquire new data of study areas.

AIRBORNE DATA

There are currently two national airborne remote sensing programs with data archived at the USGS' EROS Data Center in Sioux Falls, S. Dak. The National High Altitude Photography (NHAP) program is producing 7.5-minute quadrangle stereo photographs, and the USGS' Side-Looking Airborne Radar (SLAR) program is acquiring 1:250,000- or 1:400,000-scale radar images for the conterminous United States and for Alaska. Airborne digital multispectral and imaging spectrometer data are being collected commercially from a variety of systems such as Daedalus, Geoscan, and GER. Broadband data (comparable to MSS and TM but involving several more channels) are processed using techniques now routinely used in processing satellite data. Imaging spectrometer data (simultaneous acquisition of many very narrow spectral bands for each ground element) require specialized processing capabilities.

The National Aeronautics and Space Administration (NASA) is conducting an airborne research program that results in the acquisition of experimental data sets. Imaging spectrometer data of selected sites have been acquired from high-altitude aircraft using the Airborne Imaging Spectrometer (AIS) and its successor, the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS). Thermal Infrared Multispectral Scanner (TIMS) data are also being obtained from high-altitude aircraft and are available for general data acquisition through the National Space Technology Labs. In addition, there are commercial instruments with similar or improved thermal capabilities currently available or under development by Geoscan and GER.

GEOGRAPHIC INFORMATION SYSTEMS

Remote sensing data, because of the uniform spatial coverage, availability at different resolutions, and digital format, are becoming important data sets for geographic information system (GIS) analyses. Initially, GIS developed along two parallel but completely distinct paths. In one path, image processing (raster based) methods were employed using satellite, airborne, and digitized photographic data. At the same time, a vector-based approach was being developed using digitized maps and statistics referenced to single geographic points. Because images were stored in raster format (equispaced array) and vector-based data were stored as an array of connecting points, there was a basic incompatibility between the two approaches. Merger was sometimes accomplished by rasterizing the vector data, which resulted in a loss of spatial resolution and a significant increase in data storage. The development of high-resolution image display systems with multiple-image planes and computer software to merge raster and vector databases is removing most of these limitations.

For earth-science applications, it is now possible to overlay digitized geologic maps on remote sensing images and then drape these over topography using digital terrain data. Special-purpose displays can be produced showing various geologic attributes (resource exploration targets, earthquake epicenters, zones of unstable ground, environmental hazards, and others) superimposed on colored renditions of multispectral remote sensing data. Such a data base can also be used to detect surface attributes such as alteration zones, moisture concentrations, vegetation and soil associations, lithology, and structure. High-spectral- and spatial-resolution data from imaging spectrometers show great promise for mapping a substantial group of minerals and their associations and for estimating mineral abundance. These capabilities will be critical in future GIS applications to geologic mapping in support of resource, hazard, and environmental studies.

REMOTE SENSING COSTS

The large variety of remote sensing data sets are available at costs ranging from a few dollars per square mile for satellite digital data to a few hundred dollars per square mile for airborne imaging spectrometry. Computer processing and analysis costs routinely surpass these expenses. Effective use of remote sensing data to solve earth-science problems requires both an understanding of the current methodology and an appreciation of the most cost-effective solution.

REPORT ORGANIZATION

In the following sections of the report, we examine the use of remote sensing methods in two broad categories: geologic remote sensing, with subsections on geologic mapping, mineral resources, and energy resources; and environmental remote sensing, covering issues ranging from pollution to global change and including two related subsections on geologic hazards and water resources. The report contains some overlaps and variations in style due to the makeup of the different working groups. For most of the detailed applications, we have described the state of remote sensing capabilities along three general guidelines: (1) currently demonstrated uses based on prior experience, (2) extended uses that are either recognized as extensions of other applications or are based on currently accepted knowledge, and (3) future uses that are still in their formative stages inferred from theoretical, instrumental, and laboratory studies. The environmental geology working group, however, felt that their section would be more effectively organized along applications without separating out the capabilities. In the process of developing this report, we also identified a number of key research topics. Support of concentrated efforts and well-focused studies in these areas will be critical for future implementation of remote sensing applications. The final section of this report examines the likely advances and limitations in future research in the field.

ACKNOWLEDGMENTS

The editors would like to thank Terry Offield and Gary Raines of the USGS for their technical reviews. We are especially indebted to John Synnefakis of the USGS' Central Technical Reports Unit for his skillful efforts at making this report more accessible.

SECTION 1: GEOLOGIC REMOTE SENSING

This section of the workshop document contains the reports from the working groups on geologic mapping, mineral resources, and fossil fuels and geothermal resources. The discussion on geologic mapping includes general applications of remote sensing to lithologic and structural mapping. Much of the recent focus of remote sensing research, particularly in the USGS, has centered on mineral resource applications. Although remote sensing studies for energy exploration have been undertaken by the USGS Branch of Geophysics in the past, most of the current activity is conducted by the oil industry, consultants, universities, and other government agencies.

GEOLOGIC MAPPING

Working Group: M. Podwysocki (*Chairman*), M. Abrams, A. Barringer, D. Knepper, F. Kruse, D. Orr, and L. Rowan

Since the 1920's, when aerial photography was first used for geologic purposes, airborne remote sensing has been used to provide geologists with the synoptic view of a terrane. However, it was not until the 1930's, when black-and-white air photos became available for many parts of the country, that the use of airborne data became more common. Geologic structures could be mapped using the spatial patterns observed on the aerial photographs, and general differences could be discerned between geologic units. Projections of known faults and fractures were seen to form linear topographic features, suggesting that the structures were more extensive than previously thought. The technological advances of aerial photoreconnaissance during World War II, including the use of color and false-color photography, further broadened the geologist's capabilities for mapping geologic units and structures.

Postwar advances included the advent of the multiband camera in the late 1950's. Expansion of sensor capabilities to longer wavelengths started in the late 1950's and continued into the 1960's, yielding analog-recording, single- or dual-channel thermal-infrared scanners and side-looking radar. More recent development of digital recording capabilities and improved sensor technology have brought multispectral scanners capable of simultaneously acquiring digital data in many channels, primarily in the visible and near-infrared spectral regions, and sophisticated multiband, multipolarization digita-radar imaging systems.

DEMONSTRATED REMOTE SENSING CAPABILITIES IN GEOLOGIC MAPPING

LITHOLOGIC MAPPING

With six channels in the visible and near-infrared, image data from the Landsat TM multispectral scanner and analogous airborne systems have been successfully used for distinguishing geologic units. Because of the positions and bandwidths of the channels in the electromagnetic spectrum, broad families of minerals can be identified or distinguished based on the presence or absence of absorption features due to ferric or ferrous iron and the hydroxyl (OH) and carbonate (CO_3) radicals. Such relatively simple digital techniques as contrast enhancement of selected TM bands or the combining of band-ratio images into color composites produce images suitable for the identification or discrimination of minerals characteristic of individual lithologic units exposed over broad regions (fig. 1). High spectral and spatial resolution provided by airborne imaging spectrometer systems permits even more detailed lithologic and stratigraphic discrimination based on subtle changes in mineralogy. Because the midinfrared part of the spectrum conveys added mineralogical information, notably for silicate and carbonate minerals, merging multispectral data from this part of the spectrum with TM-like data expands the opportunity to delineate lithologic units.

The local association of plant species with lithology has been recognized by geologists for many years and sometimes forms a basis for extending field mapping. Remote sensing data can be used to detect changes in plant communities, such as differences in species composition, biomass, and canopy closure. Airborne and satellite multispectral reflection data have sometimes been used to discriminate deciduous from coniferous forests; coniferous forests of different species; deciduous forests of different species; western rangeland shrub communities; and forests undergoing stress from drought, insect damage, or anomalous metallic elements in the soil. Where lithology controls vegetation, multispectral remote sensing data offers a means of extracting geologic information for preparing lithologic maps that might otherwise be difficult to compile.

GEOLOGIC STRUCTURE MAPPING

Computer-enhanced digital images from satellite and airborne sensors provide an excellent means for mapping regional to local lithologic contrasts using traditional photogeologic interpretation techniques. The distribution of

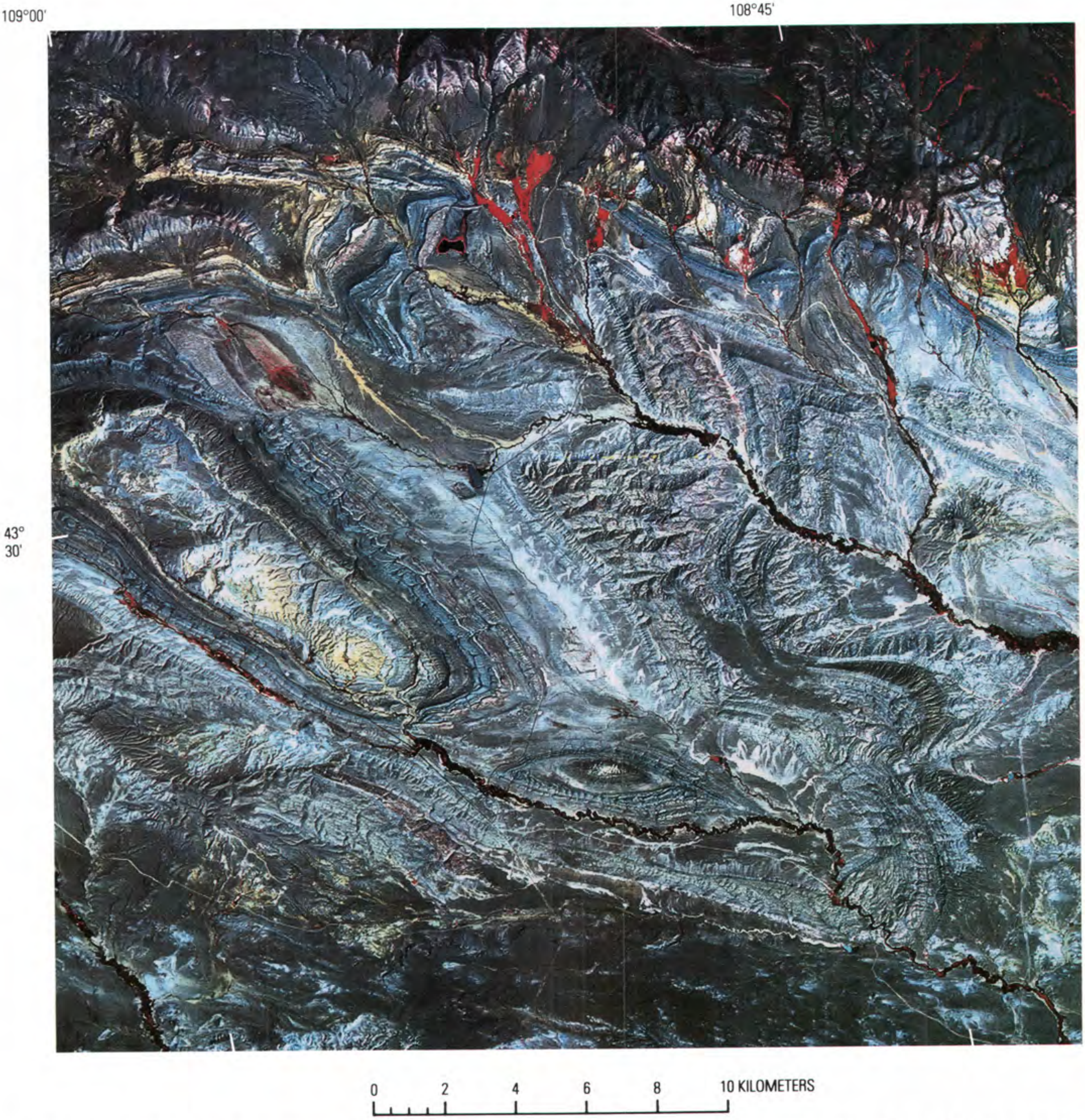

Figure 1. Landsat Thematic Mapper (TM) color-infrared composite of a portion of the northern Wind River Basin, Wyoming, showing discrimination of folded sedimentary rock units based on spectral reflectance (color) and topographic expression. Vegetation appears in shades of red, whereas red-colored rocks and soils appear yellow in the image.

various lithologic units and the geometric patterns they display commonly reveal the tectonic setting as well as local fold and fault structures. Expanded mineralogic mapping capabilities, as discussed above, can be used to prepare photogeologic and structural maps that contain significantly more information than can be obtained from comparable panchromatic or standard color air photos. Subsequent merging of these data and their derivative products with other digital data sets considerably enhances the interpretation and analysis process. Where suitable digital elevation data are available, stereographic models can also be prepared from monoscopic images of large regions.

SLAR images show features in fold geometry that result from differences in the depth to major thrust faults controlled by faults in the basement rocks located kilometers deeper (fig. 2). Field studies and examinations of proprietary seismic-reflection data indicate that thrust faults exhibiting décollement structures become shallower across lateral ramps (zones where décollements change stratigraphic level along strike). Field and laboratory studies and analyses of SLAR images show that other phenomena are also related to the positions of lateral ramps. SLAR images display discontinuities in the Blue Ridge province and in long, straight river segments emerging onto the Piedmont, Coastal Plain, and Appalachian Plateau provinces, which generally lie along interpreted lateral ramps. Interruption of Mesozoic basins by structurally high areas of Precambrian rocks, as well as zones of high seismicity, are also coincident with mapped lateral ramps. Lateral ramps are not limited to the Eastern overthrust belt but appear in many other thrust belts worldwide and have been seen on SLAR images of Papua, New Guinea, and on Landsat images of Morocco and southeastern China.

Analysis of linear structural elements of the Earth's surface using remotely sensed airborne photographs began in the late 1940's when aerial photographs first became widely available to geologists, even though lineaments reflected in topographic maps and field observations of the Atlantic border region were recognized in the early 1900's. Today, analysis of linear structural elements mapped from remotely sensed airborne and satellite data is widespread as a reconnaissance tool for determining fracture patterns on a local, regional, and continental scale in advance of field investigations for structural geology, engineering site characterizations, the study of geologic hazards, and petroleum and mineral exploration. However, despite the increased use of maps of linear structural elements compiled from remote sensing data, results of computer-automated delineation methods have not met much success and there is still much to be learned about the nature and expression of these features. Thermal-infrared data have been shown to be useful for detecting moist zones associated with fractures, but we are not aware of ongoing studies using this approach. Nevertheless, it has been repeatedly demonstrated that skilled and experienced interpreters can successfully apply linear structural-feature mapping to a variety of geologic problems at a local to regional scale.

The frequency distribution of linear structural elements in nature appears to be approximately lognormal, there being many more short elements than long ones. The longer elements (tens to hundreds of kilometers in length) are commonly called lineaments and, because of their relatively small number, are most often treated as single entities and are viewed in a regional tectonic context. There are many examples of lineaments mapped from remote sensing data and integrated into regional structural and tectonic studies, to be found in the published proceedings of the various Basement Tectonics Symposia and Environmental Research Institute of Michigan (ERIM) thematic conferences on geologic remote sensing. In different parts of the Appalachians, lineaments identified from SLAR and Landsat data have been associated with cross-strike structures, and in other areas lineaments often correspond to aeromagnetic and gravity lineaments defining deeply buried basement structure.

The shorter linear structural elements, often called linear features (<25 km long), are characterized by their relatively sharp expression on remote sensing data as opposed to lineaments, which typically have a much more diffuse expression. Linear features can be analyzed as single units or they can be treated statistically. CSIRO, a research institute in Australia, and the U.S. Bureau of Mines have successfully used individual linear features to identify and document zones of weakness that pose significant safety hazards in developing and operating coal mines. This work has been critical in demonstrating that linear features extend to depth and are not merely superficial features.

Another analytical approach is to treat the mapped linear features as a statistical sample of all linear structural elements. The data can be analyzed and grouped according to length and orientation characteristics and evaluated for domains of similar characteristics that reflect tectonic terranes and boundaries. Plots of linear-feature concentrations point toward areas where fracturing is more or less intense, a factor critical to the exploration for fracture-controlled hydrocarbon traps, hydrothermal mineralization, and groundwater. This type of analytical technique has also been used to identify zones with lineament dimensions related to buried basement structure in the Powder River and San Juan basins of the Western United States and in northern Sonora, Mexico, among other areas. In the St. Francois Mountains of southeastern Missouri, linear features analysis was instrumental in stimulating the reinterpretation of regional gravity and aeromagnetic data for previously unrecognized buried basement structure.

Geologists recognize that the morphology of the Earth's surface often reflects geologic structure. Routine and novel applications have demonstrated that satellite and airborne remote sensing data provide an effective means of extracting subtle structural information.

EXTENSIONS OF DEMONSTRATED APPLICATIONS OF REMOTE SENSING TO GEOLOGIC MAPPING

High-resolution laboratory spectral studies in the visible, near-infrared, and midinfrared (thermal) and results from geologic analyses of broadband airborne and satellite data point the way for logical extensions of existing capabilities in remote sensing for geologic mapping and for structural and tectonic analyses. Rapid technological advances in computer hardware and software during the past 10 years have provided new and powerful GISs for which remote sensing data are ideally adapted.

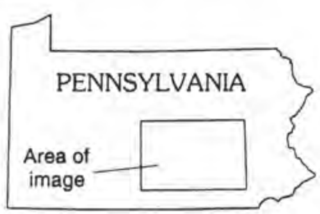

Figure 2. Side-looking airborne radar (SLAR) image of part of the Susquehanna River, southern Pennsylvania, showing fold-geometry features indicative of a lateral ramp (area bounded by solid lines). From Pohn and Coleman (1991).

LITHOFACIES MAPPING

Interpretations of broadband airborne and satellite data demonstrate that lithologic discrimination can be predicted and accomplished based on the broad spectral character of many common rock-forming, weathering, and hydrothermal-alteration minerals. Detailed laboratory mineral spectra in the visible and near-infrared have long been known to contain absorption features diagnostic of composition and molecular structure, but only recently have imaging spectrometers been developed for collecting high-resolution spectra for remote sensing applications. Although still experimental, imaging spectrometers provide the potential for extending broadband lithologic discrimination to detailed lithologic identification based on mineral content.

Previous broadband remote sensing could detect the presence of iron oxide and hydroxide minerals, but it could not determine which specific minerals were present. Imaging spectrometer data now allow diagnostic absorption bands of the various minerals to be identified and distributions of the individual iron oxide and hydroxide minerals to be mapped. This capability has direct applications to geologic mapping and the study of hydrothermal-alteration zonation. Similarly, early analysis of experimental imaging spectrometer data has shown that individual clay mineral species can be identified and mapped based on diagnostic absorption bands in the near-infrared, and that sedimentary strata composed of limestone, dolomite, and gypsum can be uniquely separated and identified. It has even been demonstrated that diagnostic absorption features associated with rare earth elements in carbonatites, the ammonium-bearing feldspar buddingtonite, varying iron/magnesium ratios in chlorite, and magnesium metasomatism in limestone can be identified from imaging spectrometer data. Clearly, the capabilities of imaging spectrometers, combined with knowledge about the many common and not so common rock-forming minerals that have diagnostic spectral features in the visible and near-infrared, are opening a new era in the application of remote sensing techniques to lithologic mapping.

Rock forming minerals such as silicates and carbonates exhibit characteristic absorption features in the 8–14 μm region. Although the spectra of rocks and soils are often complex, broadband measurements can be used to detect changes due to composition and crystal structure. For example, the intrinsic spectral features of felsic rocks occur at shorter wavelengths than those of mafic rocks. NASA's experimental TIMS is available for studying and applying this relationship to geologic problems. TIMS data have been used to indicate that broad lithologic discriminations associated with silica content are possible, which further enhances geologic mapping capabilities in most lithologic terranes. The combined application of multispectral midinfrared data with imaging spectrometer data provides more compositional information for geologic analysis than has been previously possible from airborne or satellite platforms.

STRUCTURAL ANALYSIS

Expanded remote sensing capabilities for structural studies rest on increasing the spatial and spectral resolution of the data and merging of these data with other digital data sets. Although the new breed of experimental airborne systems in the visible, near-infrared, and midinfrared have significantly improved spectral resolution, they have not appreciably increased spatial resolution compared to operational airborne and satellite systems. Consequently, additional structural information derived from these systems must come from interpretations based on greater spectral resolution of the data. This information will consist of increased detail of often subtle lithologic variations and, perhaps, better delineation of structurally controlled vegetation patterns. For example, the ability to map subtle variations in silica, limestone versus dolomite, and clay mineral content will provide tighter controls on such things as the configuration of folded and faulted strata and the internal structural fabric of plutonic rocks. In addition, broadband thermal-infrared data acquired at different times in the diurnal cycle can be used to detect moisture differences that can be useful where these differences relate to structural control.

INFERRED FUTURE USES OF REMOTE SENSING IN GEOLOGIC MAPPING

The new remote sensing tools being developed will provide the means to acquire quantitative compositional information that can be coregistered with other digital data including existing geologic maps, and terrain and geophysical data. The resulting data base will provide a wealth of information for studying structural and tectonic controls, geologic processes, and resource and environmental problems.

IMAGING SPECTROSCOPY

The capability to detect a large suite of individual minerals and possibly determine their abundance has applications to a wide variety of mapping problems. These include identifying intrusive and extrusive facies in igneous terranes, ultramafic complexes, batholiths and stocks, contact and regional facies in metamorphic terranes, and facies changes in sedimentary terranes.

The ability to map vegetation communities associated with lithofacies would be particularly valuable in highly vegetated terrain. Use of high-resolution spectral-reflectance data from imaging spectrometers may provide some capability for detecting subtle spectral changes necessary to distinguish broad planophile canopies of different species composition, although this is conjectural.

MULTISPECTRAL THERMAL IMAGING

As the capability to acquire additional spectral bands in the thermal-infrared region increases, the opportunity to

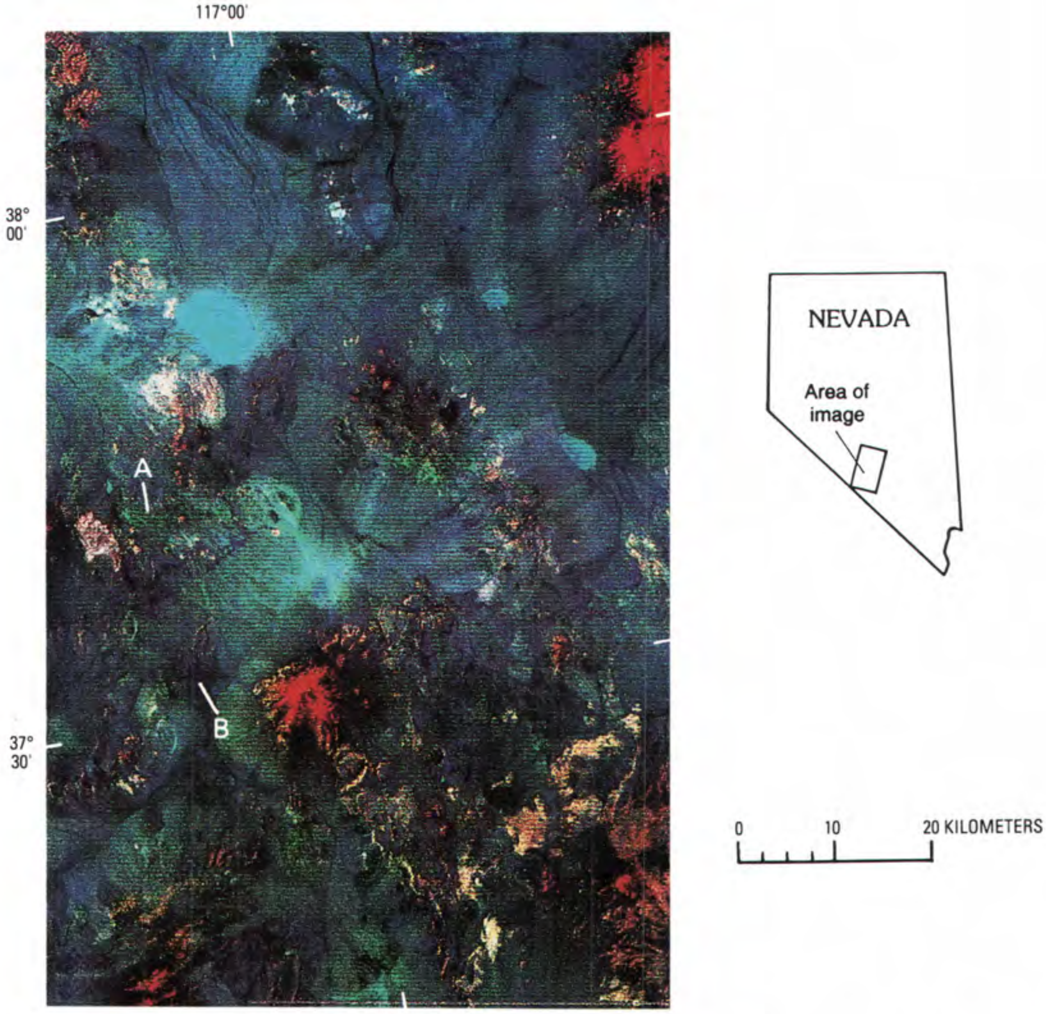

Figure 3. Regional Landsat Multispectral Scanner System (MSS) color-ratio composite of the Cuprite and Goldfield, Nevada, mining districts. **A**, limonitic altered rocks (green) in the Goldfield district. **B**, Cuprite district location containing bleached, nonlimonitic altered rocks that cannot be identified using MSS data. Courtesy of Lawrence C. Rowan, USGS.

identify carbonate, sulfate, and phosphate minerals will also increase. Subtle but recognizable spectral differences among intermediate igneous rocks will be useful for mapping in igneous terranes.

RADAR

It has already been shown that L-band (30 cm) radar can penetrate to depths of one to several meters in hyperarid terrain. Using nadir viewing systems that have greater penetration than off-nadir systems, an airborne radar profiling system might be developed to detect moisture distribution down to a depth of several meters in some arid regions of the Western United States, thus providing important structural information. In addition, radar-reflectance data may prove useful in geobotanical studies for determining leaf and needle characteristics.

MINERAL RESOURCES

Working Group: L. Rowan (*Chairman*), M. Abrams, R. Clark, A. Goetz, F. Kruse, K. Lee, R. Lyon, D. Peters, M. Podwysocki, G. Raines

Mineral resource studies have always been major users of geologic remote sensing data. The main avenue of research has been the development of methods of analyzing multispectral images for identifying lithologies and structural features that may indicate conditions favorable for deposition and concentration of minerals. This section describes the lithologic and structural mapping capabilities that (1) have been demonstrated and are being used operationally,

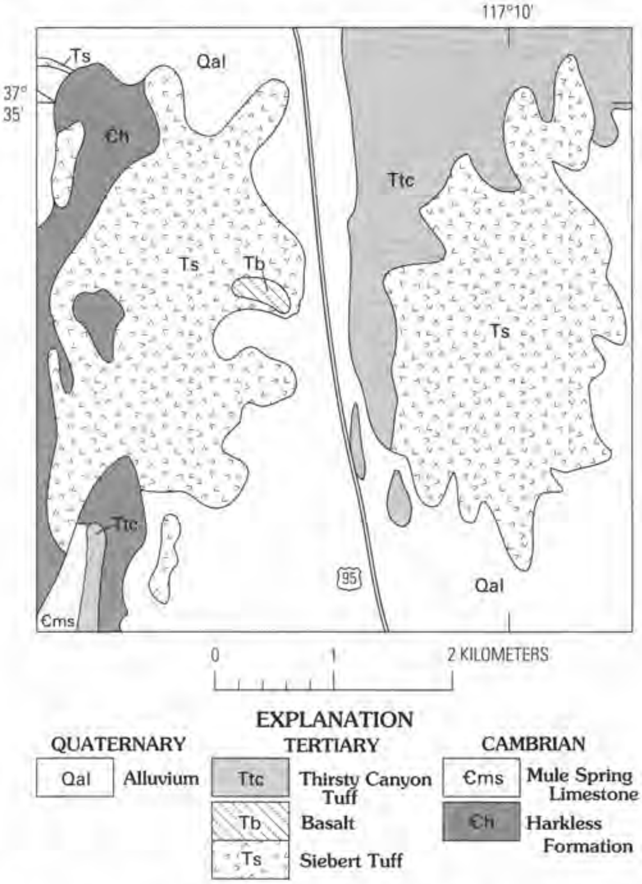

Figure 4. Generalized geologic map of the Cuprite mining district. Location of map area is shown in figure 6. Reproduced from figure 4 of the article "Mineralogic information from a new airborne thermal infrared multispectral scanner" by Anne B. Kahle and Alexander F.H. Goetz, courtesy of *SCIENCE*, v. 222, p. 27, issued October 7, 1983, © AAAS.

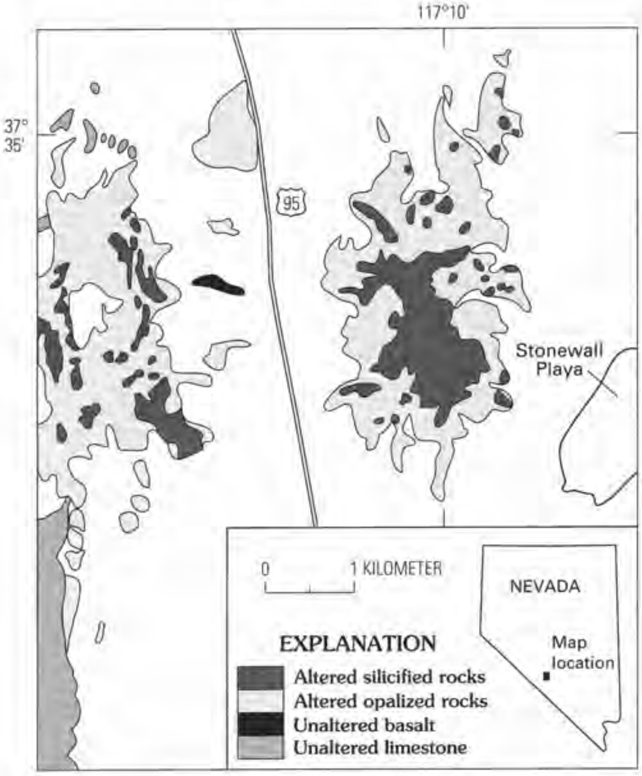

Figure 5. Distribution of hydrothermally altered and unaltered rocks in the Cuprite mining district. Location of map area is shown in figure 6. Map courtesy of Michael J. Abrams, Jet Propulsion Laboratory, from a modification of figure 2 in Ashley and Abrams (1980).

(2) are extensions of recent research using advanced airborne systems, and (3) are probable future applications based on limited laboratory and field studies.

DEMONSTRATED REMOTE SENSING CAPABILITIES IN MINERAL RESOURCE STUDIES

LITHOLOGIC MAPPING

Prior to the launch of the first Landsat satellite, an airborne experiment showed that anomalous concentrations of limonite related to oxidation of sulfide minerals could be identified and mapped on multispectral visible and near-infrared images. Analysis of a Landsat MSS image of the Cuprite and Goldfield, Nevada, mining districts confirmed the airborne results and demonstrated that the diagnostic spectral reflectance of limonite could be detected from orbit (fig. 3). Many lithologic units can be distinguished in MSS images, but the four broad spectral channels provide diagnostic compositional information only for limonite. This method for mapping anomalous limonite concentrations has been used widely in mineral resource studies for mapping hydrothermally altered rocks, but extensive fieldwork is needed for distinguishing between limonite due to oxidation of sulfide minerals and limonite resulting from weathering of mafic minerals. Another important limitation of using Landsat MSS data for mapping hydrothermally altered rocks is that nonlimonitic altered rocks such as the bleached altered rocks in the Cuprite mining district can sometimes be discriminated but not identified.

The hydrothermally altered rocks of the Cuprite district are typical of many altered areas lacking significant iron oxide minerals. Rock units exposed in the Cuprite district are Tertiary ash-flow and air-fall tuffs and basalt (fig. 4), with Cambrian siltstone, quartzite, and limestone along the western margin (fig. 5). The Tertiary ash-flow and air-fall tuffs are extensively altered and silicified, and opalized rocks are widespread, with argillized rocks present in the peripheral areas. Silicified rocks contain abundant hydrothermal quartz (cristobalite) and form vuggy, irregular outcrops locally coated with less than 10 percent dark goethite. Opalized rocks contain as much as 30–40 percent kaolinite and alunite. Argillized rocks consist of kaolinite formed from alteration of plagioclase and montmorillonite, and opal derived from glass; K-feldspar, quartz, and sparse biotite are little altered. Goethite and hematite are locally abundant in the argillized rocks, but they are generally lacking in most of the hydrothermally altered rocks. Remote sensing data acquired at longer wavelengths than the MSS data are necessary for detecting and mapping hydrothermally altered rocks without significant iron oxides, like those present in the Cuprite district.

The addition of two spectral channels in the Landsat TM system at wavelengths longer than the four MSS channels provides sensitivity to absorption in clay minerals and other hydroxide (OH-bearing) minerals that are common in hydrothermally altered rocks. The opalized and argillized rocks in the Cuprite district appear distinctive in a TM image (fig. 6) due to Al–O–H absorption in kaolinite and alunite; in contrast, the silicified rocks are not distinctive because of their low OH-mineral content. Limonitic hydrothermally altered rocks containing OH-bearing alteration minerals are also distinguishable in this TM image, especially in the Goldfield mining district. Although Landsat TM images are useful for regional mapping of hydrothermally altered rocks, airborne TM (TMS) images such as that of the Cuprite district (fig. 7) are more useful for district-scale studies. TMS images are being acquired by NASA and private contractors. However, an important limitation is that mineral identification other than for limonite and the OH, HOH, and CO_3 minerals is not feasible because of the use of broad spectral channels. Consequently, separation of hydrothermally altered rocks from carbonates, shales, and other rocks that have minerals with absorption features near 2.2 μm and 2.35 μm is not possible with TMS. Therefore, field evaluation is necessary to resolve such ambiguities.

Most remote sensing studies of hydrothermally altered rocks have been conducted in the Western United States because of program demands and good rock exposure. However, studies in the North Carolina slate belt have demonstrated the usefulness of TM images for detecting spectrally anomalous soil that was derived from potassic altered rocks. These results have been used to guide detailed field mapping and geochemical sampling that have led to development of a new model for gold mineralization in the slate belt. Because the soil is turned up in plowed fields, high spatial resolution and seasonal data acquisition are important for mapping these soil exposures.

In densely vegetated areas, species composition and density variations can sometimes be used as indirect means of mapping lithologic differences. Examples that have been recognized for many years are the association of coniferous trees with arenaceous rocks in the Appalachians, and low vegetation density on ultramafic areas. More specific associations in mineralized areas are found in the East Tintic, Utah, mining district, where a lower density of sagebrush grows on argillized volcanic rocks than on unaltered rocks, and in altered areas of the Virginia Range in Nevada and Big Rock Candy Mountain, Utah, where anomalous growths of Ponderosa pine trees are observed together with a very low sagebrush density. These vegetation variations can be mapped in Landsat MSS images because of their spectral contrast with respect to the surrounding vegetation. Landsat TM and TMS images provide additional spectral and spatial detail that may be useful for mapping vegetation anomalies, especially at district scale.

STRUCTURAL FEATURES

Landsat MSS and TM images are used in mineral resource studies for mapping linear features that provide information about the regional structural framework and for recognizing the association of some mineral deposits with fractures and their continuity to depth. One dramatic, often-cited example was the use of photolineament studies (together with aeromagnetics) in the discovery of the Olympic Dam deposit in Australia. SLAR images that have been acquired by the USGS for 1°×2° quadrangles provide information about topographically expressed fractures. Broad-band thermal-infrared images are useful for detecting fracture zones that concentrate moisture in the soil. All these types of images are used operationally in mapping structural features in mineral resource studies. However, the resulting structural information generally constitutes only one element of the data set used in resource assessment and must be evaluated in conjunction with other elements such as host and source rocks, and subsurface (depth) constraints deduced from geophysical data.

EXTENDED REMOTE SENSING CAPABILITIES IN MINERAL RESOURCE STUDIES

Recent research using advanced experimental imaging systems has resulted in development of methods for making compositional determinations that are not possible using operational satellite systems such as Landsat MSS and TM and airborne systems such as TMS. The most important advanced systems are airborne imaging spectrometers that record reflected energy in numerous narrow channels throughout the 0.4–2.5 μm (visible and near-infrared) region, and TIMS, which records emitted energy in the 8–14 μm (thermal infrared) region. The compositional information available in these two wavelength regions is complementary and some of the determinations that are possible, such as the identification of small but significant amounts of buddingtonite, pyrophyllite, and bastnaesite, are not even feasible using conventional field procedures. Compositional variations that are directly relevant to the formative conditions of mineral deposits can be mapped and evaluated rapidly by analyzing data acquired with these advanced systems.

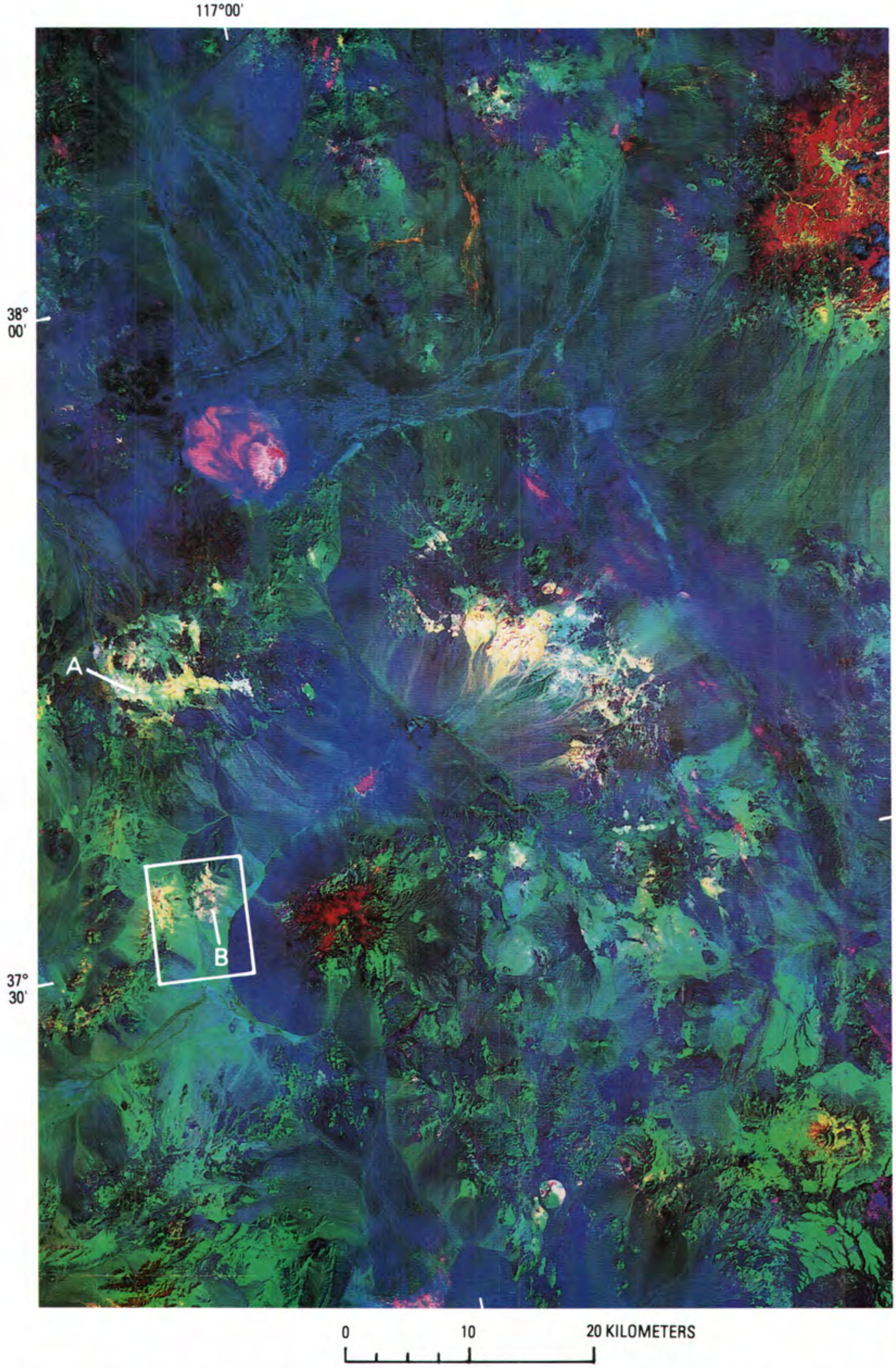

Figure 6. Regional Landsat Thematic Mapper (TM) color-ratio composite showing (**A**) limonitic altered rocks containing OH-bearing minerals in the Goldfield district, and (**B**) nonlimonitic opalized and argillized rocks containing OH-bearing minerals in the Cuprite district. Area in box shows location of figures 4,5,7, and 10. Areal coverage of this image is the same as the MSS image in figure 3. Courtesy of Fred A. Kruse, University of Colorado.

Figure 7. Thematic Mapper Simulator (TMS) color-ratio composite of the eastern part of the Cuprite district. Magentas, reds, and yellows are opalized rocks; dark reds and browns are silicified rocks; yellow-greens are argillized rocks; dark greens to dark blues are unaltered volcanics; and light blues are playa deposits. Location of image area is shown in figure 6. From Abrams and others (1977).

The spectral reflectance and emittance features that are measured by advanced systems and analyzed for compositional determinations were discussed in the Geologic Mapping section of this report. These determinations can be used to identify mineral suites that characterize alteration zones. In such a zone, hydrogen-ion activity increases from a low level in the propylitic zone to a high level in the low-temperature advanced argillic zone. The stability ranges of many of the alteration minerals present are shown in figure 8.

The Cuprite mining district contains most of the mineralogic characteristics of a hot-spring deposit, including intensely leached silicified rocks in the central part, kaolinite and alunite in the opalized zone, and, locally, buddingtonite (fig. 5). Analysis of high-spectral-resolution data of the eastern part of the district, recorded by NASA's AVIRIS, shows that alunite, kaolinite, and buddingtonite can be identified based on their visible and near-infrared reflectance spectra (fig. 9). These results have been confirmed at Cuprite through analysis of commercial imaging spectrometer data that have lower spectral resolution but higher radiometric sensitivity than the AVIRIS system. In addition, the Si–O–H feature exhibited by opal in near-infrared spectra was identified in the opalized rocks (fig. 8).

Quartz lacks diagnostic visible and near-infrared absorption (except for the Si–O–H feature in opal), but in the thermal-infrared wavelength region, quartz has an intense Si–O–Si emission feature that allows identification of quartz-rich rocks. This capability is important for identifying silicified rocks, which commonly lack OH-bearing minerals. In some deposits, silicified rocks are the only altered rocks that are exposed because of their resistance to erosion. Analysis of a TIMS image of the Cuprite district (fig. 10) was used to map the silicified zone, which is not distinctive in the TM and AVIRIS data. Thus, multispectral thermal-infrared, visible, and near-infrared data are complementary and, used together, they provide the means for rapidly mapping compositional variations that define alteration zones and for identifying many different rock types.

Results obtained through analysis of TM images of areas in Nevada and Spain indicate that reflectance differences between contact-metamorphosed slate and stratigraphically equivalent regionally metamorphosed (greenschist facies) slate can be used to map contact aureoles, including aureoles related to shallowly buried intrusives. The contact-metamorphosed slate has lower reflectance (especially in the near-infrared wavelength region) due to thermal maturation of contained organic matter. Similar reduction of near-infrared reflectance has been noted in carbonate-rock spectra where the rocks have been subjected to anomalously high paleotemperatures. These results suggest that TM and its airborne equivalent TMS may be useful for detecting shallowly buried intrusive bodies and, therefore, may aid in assessment of mineral resources that commonly occur in contact-metamorphic zones. Because of the high spectral-reflectance contrast between vegetation and these and most other rock types, the high spatial resolution provided by TMS images is important.

FUTURE REMOTE SENSING CAPABILITIES IN MINERAL RESOURCE STUDIES

Several remote sensing methods appear to have considerable potential for mineral resource studies, but they have not been demonstrated fully due to unresolved questions about the processes that produce the observed variations or the geological interpretation of the observations. Additional research may bring these methods to the applications stage, thus making substantial contributions to mineral resource studies.

GEOLOGIC PROCESSES

Demonstrated and extended capabilities of remote sensing in mineral resource studies clearly point toward an increasing role for detailed spectral analysis of airborne

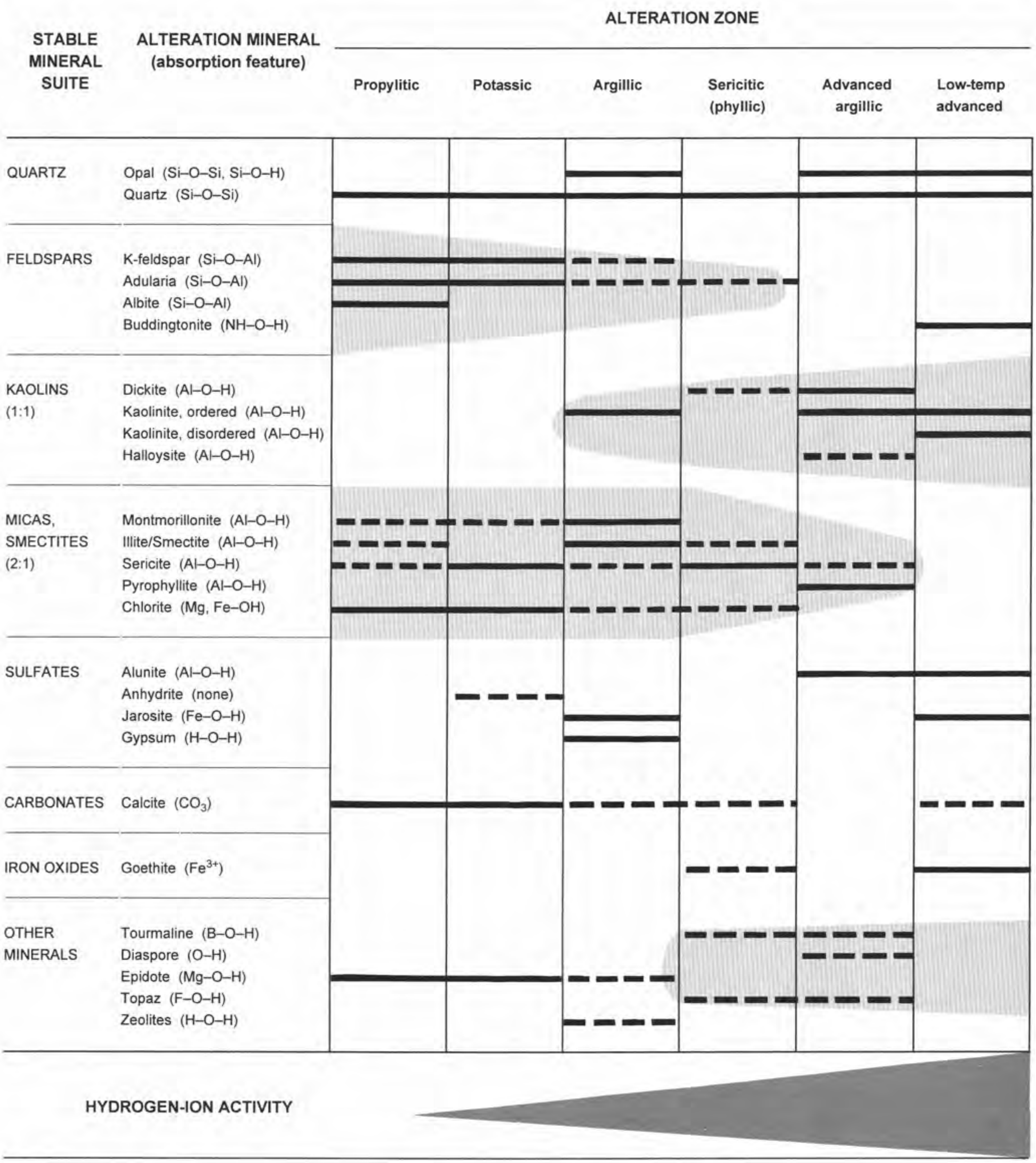

Figure 8. Stability ranges of minerals in alteration zones such as those found in the Cuprite mining district. Solid lines indicate stable alteration minerals; dashed lines show where minerals may be present. Screened areas are stability ranges of mineral suites. Absorption features can be detected using advanced imaging systems.

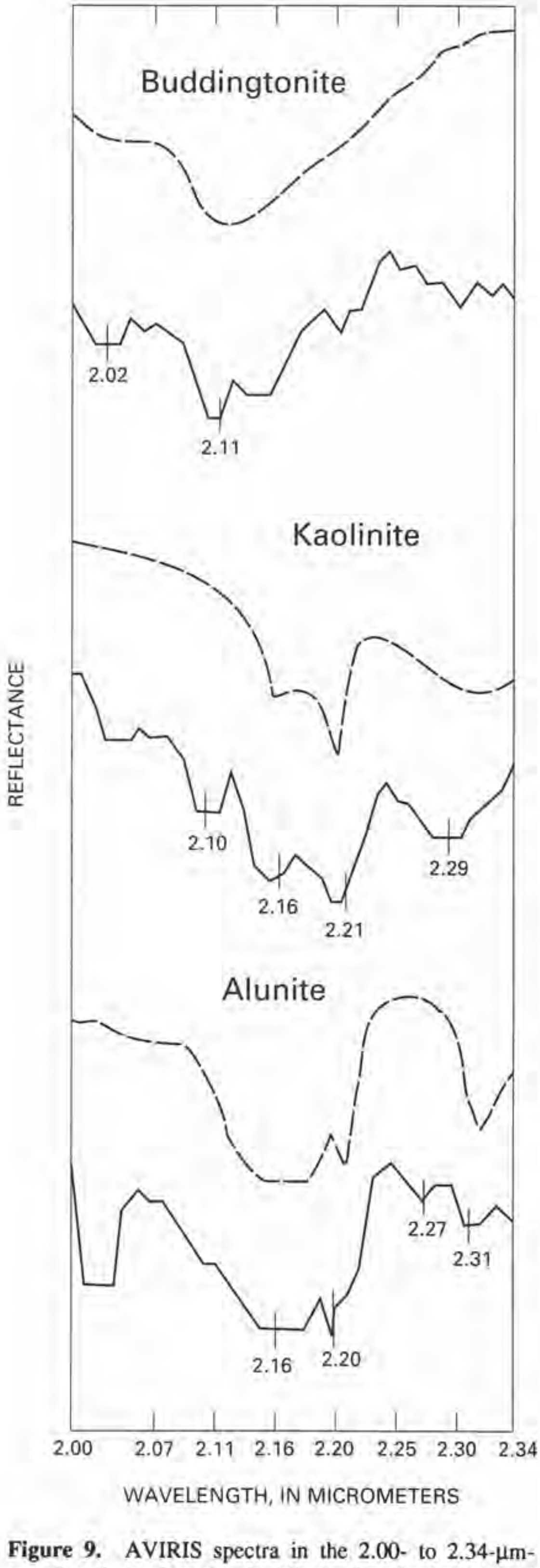

Figure 9. AVIRIS spectra in the 2.00- to 2.34-μm-wavelength region for buddingtonite, kaolinite, and alunite from the Cuprite district (dashed lines) compared to laboratory reflectance spectra (solid lines). Spectra are separated for ease of comparison only and do not represent absolute reflectance values.

imaging spectrometer and multispectral thermal-infrared data in future mineral exploration and assessment programs. These types of sensing systems will eventually be placed in orbit and the availability of high-spectral-resolution data will be worldwide. Advances in computer power and analytical software will be necessary for analyzing the large volumes of detailed data produced by these systems in an efficient and timely manner.

Present capabilities of imaging spectrometer and multispectral thermal-infrared data in mineral resource studies deal largely with a select group of minerals and general rock types in limited geographic areas. Advances in sensor technology will increase the signal-to-noise ratio of imaging spectrometer data and increase the spectral resolution of multispectral thermal-infrared data, which will lead to an increase in the capability of detecting subtle spectral characteristics of a wide variety of minerals. This will lead to more detailed identification of soil and rock mineralogy, promoting a greater understanding of hydrothermal, igneous, and other geologic processes.

To cope with future enhanced sensor and computer technology and large volumes of data, research must address the development of detailed and efficient processing and analysis techniques and the interpretation of their data in the context of mineralizing systems. In addition, the theory of mineral-mixing models must be developed into operational techniques that allow mineral grain size and abundance to be determined directly from remote sensing data.

LINEAMENT AND LINEAR-FEATURE ANALYSIS

Geologic structure has long been known to affect and (or) control the location and emplacement of mineral deposits. The "plumbing system" provided by such structure affects the movement of mineral-rich fluids and may provide the site of deposition of minerals due to pressure, temperature, or chemical environment changes present along structural pathways. In line with this association of mineral deposits and geologic structures, linear structural elements on the Earth's surface have been used as conceptual and actual exploration guides to define geologic structure and, therefore, as areas potentially favorable for deposits. Various scales of linear elements have been used for this purpose, from linear features of very narrow extent used to define a local "plumbing system" for a single deposit or mineral district, to regional- and even continental-scale lineaments, which may be indicative of major tectonic provinces or deep crustal discontinuities that may control entire collections of mineral districts and emplacement of whole mineral associations.

However, the use of linear elements as guides to potential mineral deposits has not been without controversy. Regional-scale lineaments are commonly difficult to identify on the ground because their geologic expression

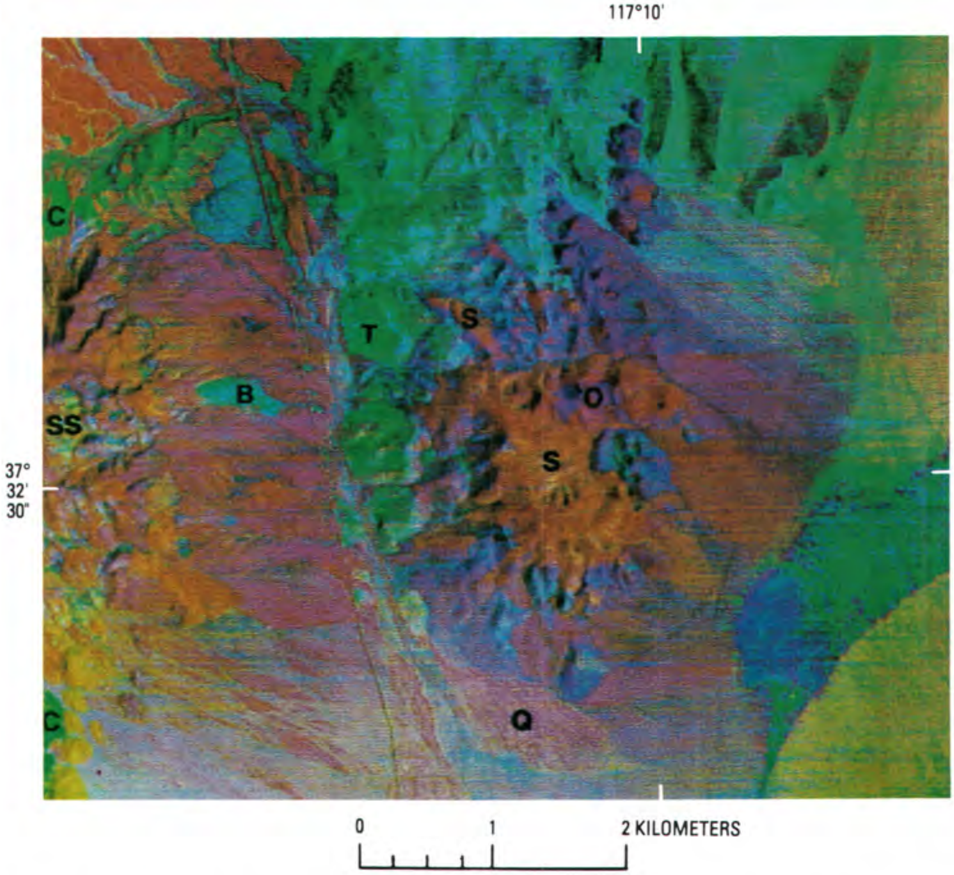

Figure 10. Thermal-Infrared Multispectral Scanner (TIMS) color composite of the Cuprite district showing silicified (bright orange) and opalized (magenta) rocks. **B** is basalt; **C**, carbonate; **O**, opalized rock; **Q**, alluvial fan; **S**, silicified rock; **SS**, siltstone; and **T**, unaltered tuff. Location of image area is shown in figure 6. Reproduced from figure 3 (bottom) of the article "Mineralogic information from a new airborne thermal infrared multispectral scanner" by Anne B. Kahle and Alexander F.H. Goetz, courtesy of *SCIENCE*, v. 222, p. 26, issued October 7, 1983, © AAAS.

typically varies, and along some segments (such as linear stream channels) evidence in the bedrock is obscured. Geophysical data are particularly important in these areas and, in many cases, provide evidence of continuity in the subsurface.

On a more local level, linear features can indeed be used as indicators of specific geologic structures such as faults, joints, and fracture zones that extend to some depth. Studies in coal mining areas have shown that individual linear features identified on Landsat images can be traced to fractures, faults, and probable fracture zones found in mines at depths of 450 m and more. This correlation is possible even though many of these linear features are difficult or impossible to identify as specific geologic structures at ground level. Similarly, it should be expected that, for mineral deposits, linear features identified through remote sensing will to a large extent be related to subsurface structures that may have been formed during mineral deposition or that may have had some control on such deposits.

GEOBOTANY

Geobotanical studies are being conducted with two main objectives: (1) to study the relationship between lithologic composition and geographic plant distribution and element uptake, and (2) to determine if it is possible to develop remote sensing techniques for mapping the distribution of plants, especially those that are important to mineral resource studies. Within a particular climatic zone, the principal factors that control plant physiography are topographic elevation, soil moisture, nutrients, and, of course, human activities. The interaction of all these factors is complex, but soil moisture and nutrients can be studied independently in areas where variations in topographic elevation and levels of human activities are small.

Two avenues of geobotanical research that have produced promising but incompletely understood results are the association of a plant community in the North Carolina slate belt with lithologies that are important for gold exploration, and the detection of metal-stressed vegetation in several areas having coniferous and mixed deciduous tree cover. Digital classification of Landsat MSS and TM images of the North Carolina slate belt shows that predominantly chestnut oak forests are spatially associated with high-alumina quartz granofels, silicic volcanic rocks, and certain granitic rocks. Gold deposits occur within or near areas consisting of quartz granofels and silicic volcanic rocks, as well as in areas of potassic altered rocks that do not have chestnut oak forests but that produce spectrally anomalous soil. In the Piedmont province in Virginia, chestnut oak forests are also associated with metavolcanic rocks having high silica concentrations and with Tertiary gravel deposits, the gold deposits occurring mainly in the metavolcanic rocks. These botanic-lithologic associations are believed to be due to the tolerance of chestnut oak trees to dry conditions and to high silica and aluminum concentrations, but more research is needed to relate the soil geochemistry to species distribution. An important goal of geobotanical research in eastern United States forests would be to relate plant species distribution to spectral properties of forests in other climatic zones, such as the Northeastern United States.

Plants that exist in dynamic equilibrium with the substrate are natural subsurface geochemical samplers. They commonly reflect geochemical soil anomalies by: (l) the anomalous distribution of species or plant communities, (2) stunted growth or decreased areal distribution, (3) changes in leaf pigmentation and transpiration rate, and (4) changes in the phenological cycle that cause early senescence, late leaf flush, and alteration of flowering periods. Some conspicuous manifestations of geochemical anomalies have been detected on the ground and in conventional aerial photographs, but the subtle or seasonal manifestations that aid in identification of buried deposits requires the use of modern remote sensing techniques. Multitemporal remote sensing is especially well suited for studying anomalous phenologic cycles, but airborne images that provide adequate multitemporal coverage are not generally available.

The typical visible and near-infrared reflectance spectrum of a healthy photosynthesizing plant (fig. 11*A*) exhibits chlorophyll and other plant-pigment absorption features centered near 0.68 µm and 0.48 µm, high reflectance centered near 1.0 µm due to cell morphology and leaf internal refractive discontinuities, and water absorption at longer wavelengths: the 1.6 µm region is especially sensitive to leaf water content. Laboratory experiments have shown that concentrations of certain metals in the growing medium cause the steep part of the spectrum between 0.68 and 0.76 µm to shift to shorter wavelengths, a phenomenon commonly referred to as the "blue shift of the red edge." However, high-spectral-resolution measurements are needed to detect this 0.007–0.010 µm shift.

Analysis of high-spectral-resolution data acquired using a commercial airborne profiling spectrometer has demonstrated the spatial coincidence of the "blue shift of the red edge" with metal concentrations in different geologic settings and tree cover types in the following locations: (1) Cotter basin, Montana, where silver, copper, lead, zinc, and gold occur in veins in Precambrian metasedimentary rocks with coniferous tree cover, (2) Goat Mountain, Wash., with copper sulfides in a small phyllic zone in silicified and argillized breccia and dense coniferous tree cover, (3) Pilot Mountain, N.C., with copper, molybdenum, and tin in quartz granofels and quartz-sericite-pyrite altered rocks and a

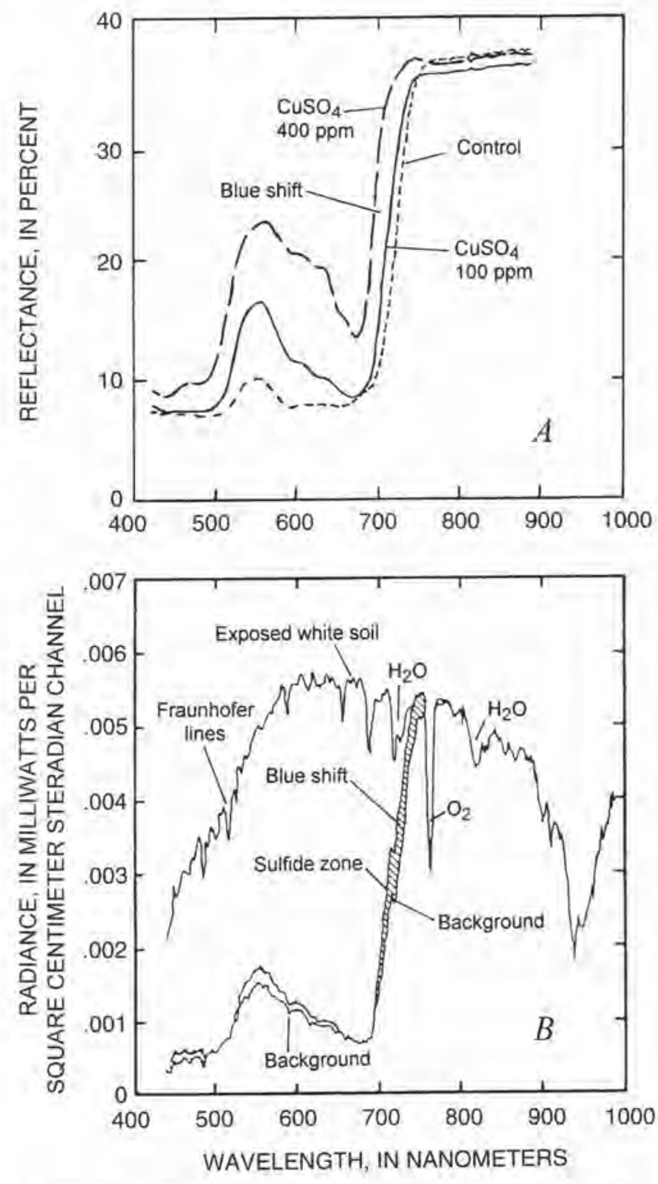

Figure 11. Geobotanical reflectance spectra showing the "blue shift of the red edge" effect in the 0.68–0.76 µm region for: *A*, sorghum grown in media to which 0 ppm (control), 100 ppm, and 400 ppm Cu was added as $CuSO_4$ (from Chang and Collins, 1983); and *B*, airborne spectrometer data of background and anomalous trees in the Cotter basin, Montana, area (from Collins and others, 1983). Reproduced from *Economic Geology*, 1983, v. 78, p. 728 and 743.

mixed deciduous forest consisting mainly of chestnut oak trees, and (4) Cuttingsville, Vt., where molybdenum, arsenic, bismuth, copper, and gold are concentrated in alkalic igneous and metasedimentary rocks in an area with mixed deciduous trees. In the Cotter basin, the areas exhibiting the blue shift in the initial 1976 survey were remapped successfully in 1978. These test results indicate that coniferous and deciduous trees growing in soil that has concentrations of base and precious metals exhibit a subtle spectral-reflectance shift that can be detected using an airborne spectrometer.

Although these results appear to demonstrate the feasibility of airborne reflectance spectrometers for mapping vegetation-covered mineral deposits, the following aspects must be addressed before this technique can be applied operationally: (1) types and concentrations of base and precious metals that cause metal stress in plants, (2) effects of other soil components such as other metals and moisture availability, (3) optimum seasonal and diurnal periods for airborne surveys, (4) spectral-resolution and radiometric sensitivity requirements, (5) development of analytical procedures, and (6) understanding of the mechanisms that cause spectral change in plants.

FOSSIL FUELS AND GEOTHERMAL RESOURCES

Working Group: D. Knepper (*Chairman*), A. Barringer, A. Kahle, R. Reynolds, J. Turner, R. Vincent

Because the primary focus in energy resource exploration has been seismic (largely due to the focus on oil and gas), remote sensing has been generally limited to examination of the regional geologic setting using conventional photogeologic interpretation. Recently, however, there has been an emphasis on identifying subtle surface changes that might be indirect indicators of a buried deposit. These can include changes in the surface mineralogy, vegetation patterns, surface temperature and, in some instances, a complex combination of all three. Because the changes are small and best observed (in most cases) in spectral regions beyond the visible, they require use of state-of-the-art instruments and data processing and analysis techniques.

DEMONSTRATED REMOTE SENSING CAPABILITIES IN ENERGY EXPLORATION

GEOLOGIC MAPPING

Airborne multispectral scanner data from TMS and TIMS have been used to prepare detailed and reconnaissance geologic maps, particularly in poorly mapped or unmapped areas. These data have been specially processed to provide appropriate images for geologic mapping including principal components, edge enhancement, and color composites of separate bands or ratios. Interpretation of the processed images has been primarily conducted using photogeologic techniques.

SLAR has been used to map local and regional topographically expressed features that reflect geologic structures important to the accumulation of petroleum deposits. In studies of the Appalachian Mountains, SLAR images were used to identify and map lateral ramp structures (fig. 2) that have a direct bearing on the localization of petroleum deposits, as well as the tectonic evolution of the folded thrust belt.

HYDROCARBON MICROSEEPAGE DETECTION

Specially processed TMS images, along with Landsat MSS images, have been used to identify and map bleached zones attributed to the seepage of hydrocarbons in sandstones of the Paradox basin, Colorado and Utah, and the Cement field, Oklahoma. The bleached rocks contain substantial amounts of kaolinite and minor amounts of feldspar, whereas equivalent unbleached rocks have much less kaolinite and abundant feldspar.

MAPPING IRON OXIDES

Escaping hydrocarbons, when mixed with ground water, can yield fluids that reduce ferric iron to the ferrous state, whereby the iron becomes soluble in the reducing fluid. After upward migration to near-surface oxygenated ground waters, this transported iron can be precipitated as pyrite, which can then be weathered to ferric oxides in an oxygen-rich environment. This process can remobilize iron, and the surface manifestation will depend on whether the shallow-buried rocks (or residual soils derived from them) were below (bleached of ferric oxides) or above (locally enriched in ferric oxides) the ground-water table at the time of the seep.

Landsat MSS and TM data have been used as petroleum exploration tools to map anomalous local occurrences or absences of ferric oxides in semiarid terrain for over 10 years. Although it is impossible to discriminate primary from secondary ferric oxides in most locations using MSS data, correlations between oil fields and ferric-oxide occurrences (as seen in spectral-ratio images produced with MSS data) have been noted by numerous companies over the years. Corroborating evidence is needed in almost all petroleum exploration cases.

GEOBOTANICAL INDICATIONS OF HYDROCARBONS

At least two petroleum exploration companies are known to be using geobotanical indicators for operational hydrocarbon exploration, and studies by the Joint NASA/Geosat Test Case Project addressed numerous potential remote sensing applications in energy exploration. The Geosat Committee, Inc., is a nonprofit consortium of private companies that promotes the use and development of space technology for geologic applications.

Two Geosat test sites, Lost River, W. Va., and Patrick Draw, Wyo., showed well-documented geobotanical effects caused by natural-gas seeps. At Lost River, maple trees grew where they ordinarily were absent, and at Patrick Draw, sage was stunted over areas through which natural gas has seeped. Tree morphology and rare-grass-species occurrences are two types of geobotanical indicators now showing promise as petroleum exploration tools. At Patrick Draw, a principal-component image of TMS data revealed a tonal anomaly situated directly above the hydrocarbon-reservoir gas cap. Field inspection found stunted sagebrush and unusually alkaline soils in the anomalous area. Whereas additional research is necessary to establish a clear cause-and-effect relationship, it appears that the local seepage of hydrocarbon gasses has affected both vegetation and soil conditions in the area.

Subtle vegetation effects related to the presence of local toxins such as migrating hydrocarbons may also be revealed using multispectral data or multitemporal methods. One such method for detecting vegetation stress involves principal-component analysis of registered, near-infrared MSS bands taken from several data sets acquired during a growing season. Subtle vegetation changes such as late green-up or early senescence may indirectly reflect the presence of hydrocarbons. The potential of geobotanical indicators that can be detected by remote sensing means has not been clearly documented. Their use as a possible exploration tool for evaluating Federal lands remains under investigation.

GEOTHERMAL RESOURCES

Remote sensing techniques can be used to study relationships among surface heat flow, regional structure, ground-water movement, and rock composition and also to map altered rocks and zoned mineral assemblages. The capability now exists of combining data from experimental airborne systems with satellite data of proven capabilities for lithologic discrimination and for mapping of structural setting. New developments in imaging spectroscopy, multispectral and multitemporal thermal data, and geographic information systems analysis provide a unique opportunity for geothermal exploration. These methods can be used to (1) detect epithermal minerals, (2) map silicification, (3) identify ammonium-bearing minerals, (4) discover anomalous surface heat fluxes, and (5) recognize thermal metamorphism.

Epithermal minerals have diagnostic spectral features in the near-infrared that can be detected using imaging spectroscopy. Silicification is often associated with active hydrothermal systems, and by exhibiting diagnostic spectral-emissivity features, silicates have been mapped using TIMS. Ammonium-bearing minerals, associated with geothermal activity where organic-rich shales are present, have also been detected and mapped using imaging spectroscopy. Some of the earliest applications of remote sensing involved thermal-infrared studies of active geothermal areas such as Yellowstone and the Geysers. Our understanding of geothermal processes can be enhanced by increasing the sensitivity of instruments to detect very subtle geothermal anomalies. Repetitive surveying, high spatial and thermal resolution, and complex modeling are required to reduce the geologic, topographic, and meteorologic noise factors. Thermal metamorphism in some cases can also cause reductions in spectral contrast and albedo, changes that are detectable using airborne multispectral scanners.

EXTENDED REMOTE SENSING CAPABILITIES IN ENERGY EXPLORATION

MAPPING CARBONATE LITHOLOGIES

Analyses of airborne imaging spectrometer data have shown that calcitic and dolomitic limestones can be identified and differentiated due to subtle differences in spectral absorption in the 2.35 μm region. This capability can be extended to the identification of sedimentary facies affecting petroleum accumulations and to possible carbonate accumulations associated with microseepage phenomena. Carbonate rocks can be discriminated on Landsat TM images and, consequently, should also be mappable in more detail using TMS.

SURFACE-OIL DETECTION

The distribution patterns of escaping oil from a seep in an ocean environment and from an oil well blowout in a marsh have been directly detected using data from experimental line and imaging Fraunhofer Line Discriminator (FLD) systems. The systems detect fluorescence by measuring ratios of very narrow spectral features in the solar spectrum. Other applications in the exploration and assessment of oil accumulations might also be possible.

GIS DATA INTEGRATION

Geographic information systems (GIS) represent various digital data sets that are registered to one another according to location, forming informational layers in a single data base. These data sets commonly include cartographic, geographic, geologic, and landcover information. GIS data can be easily integrated with digital images, resulting in many extended applications. Detailed and accurate base maps could be customized by using digital images and superimposed location grids. These types of maps would be extremely valuable in areas where poor mapping or no mapping exists. Stereo images can be used to estimate elevation.

Various geologic and geophysical data can be overlain on images to facilitate integrated geologic interpretations. Also, registered digital geologic, geophysical, and geochemical data may be combined with images for statistical manipulation and analysis.

LASER REFLECTANCE SPECTROMETRY

Another promising sensor under development for exploiting spectral features is the laser reflectance spectrometer. The passive scanners that have already been discussed are limited by signal-to-noise considerations to bandwidths of approximately 0.1 µm and must look for small, subtle spectral-emittance differences superimposed on a large thermal-radiance signal. On the other hand, active instruments such as lasers, which are essentially monochromatic, are detecting relatively small spectral-reflectance differences with an excellent signal-to-noise ratio and without the contamination introduced by surface temperatures. Limitations on the active sensors are in the restricted wavelength intervals of laser systems. These intervals may be extended with the use of different isotopes of the laser material.

FUTURE REMOTE SENSING CAPABILITIES IN ENERGY EXPLORATION

METHANE IMAGING

Methane and other hydrocarbon gases have fairly distinct spectral signatures in the thermal-infrared region of 3–14 µm. Methane has a strong absorption band between 3 and 4 µm, which is a "window" region under normal atmospheric conditions. It is possible that a multiple-channel thermal-infrared scanner could map two-dimensional "clouds" of methane or other hydrocarbon gases if channels are selected to detect spectral absorption by these gases. The Atlantic Richfield Corp. once had a patent for mapping methane in such a manner, but the patent ran out before modern multispectral thermal-infrared scanners became available for widespread use. The USGS should be aware that this capability may be possible with the proper infrared sensor, particularly one that splits the 3–5 µm region into two or more bands. The detection of methane over potential wilderness areas and outside of areas containing methane-producing bogs would indicate the possible presence of leaky hydrocarbon reservoirs. This is a technique that could also be used offshore.

HIGH-RESOLUTION DIGITAL TERRAIN MODELS

Parallax in overlapping digital satellite and airborne image data can be used to produce a digital topographic model of the imaged terrain. This has several implications for energy resource exploration. First, digital terrain models (DTM) greatly facilitate the integration of data from different data sources (airborne, satellites, and maps) into a GIS data base because they permit geometric corrections for imaging parallax caused by topographic relief. Second, the high-resolution DTM can be used to produce shaded-relief images, which have proved to be very useful for mapping subtle topographic expression that can indicate structural controls. Third, high-resolution DTM makes possible the production of simulated perspective view images, which can be most helpful in examining the three-dimensional topography of an area. Fourth, the elevation data can be combined with remote sensing images to identify the attitude of geologic horizons.

HIGH-RESOLUTION THERMAL-INFRARED SPECTROMETERS

Laboratory spectra indicate a wealth of spectral features in many important minerals and rocks in the 8–14 µm atmospheric-window region. Included are diagnostic features for silicates, carbonates, sulfates, and various oxides. Currently, only broad groups can be identified, such as mafic versus felsic and silicate versus carbonate. The development now under way of higher spectral-resolution (0.1 µm) airborne thermal-infrared multispectral images eventually will allow very fine discrimination among geologic units and greater identification of rock types than is now possible.

SECTION 2: ENVIRONMENTAL REMOTE SENSING

Under the broad category of environmental remote sensing we have included the reports from three subgroups: environmental geology, geologic hazards, and water resources. These are areas that are receiving greatly increased attention with the recent focus on global climatic change and a broad range of environmental site issues. This report recognizes these as topics of increasing importance that until recently have not received as much attention as other areas in the physical sciences, such as mineral exploration. As a result, the ideas proposed are often extrapolations from other applications.

ENVIRONMENTAL GEOLOGY

Working Group: A. England (*Chairman*), A. Gillespie, T. Mace, M. Nyquist, D. Orr, T. Ridley, C. Stanich

The characteristics of an ideal environmental remote sensing system are high spatial resolution, high sensitivity to changes in baseline characteristics, proven and accessible technologies, and low cost. In practice, the most widely used technologies are often only adequate, rather than elegant. For example, because airborne photography is familiar and relatively inexpensive, it is ubiquitous in environmental studies despite obvious limitations—awkward archiving, lack of spectral resolution and sensitivity, and difficult integration with correlative GIS data. However, as automated data management and analysis becomes the norm, digital technologies will increasingly replace film-based systems.

Environmental studies commonly require baseline information about topography, geography, land cover, and land use. Aerial photographs have been acquired over areas of the United States for a variety of mapping, resource inventory, and research activities since 1940. Perhaps the most extensive collections exist at the USGS' EROS Data Center in Sioux Falls, S. Dak., and at the U.S. Department of Agriculture (USDA) Aerial Photography Field Office in Salt Lake City, Utah. Other Federal agencies, such as the U.S. Forest Service, U.S. Fish and Wildlife Service, and Bureau of Land Management, and State agencies also are sources of historical aerial photographs. The NHAP program was a Federal multiagency activity that began in 1978 to provide complete coverage of the conterminous United States periodically. It has now been superseded by the National Aerial Photography Program (NAPP).

Using NHAP, the USGS systematically acquired black-and-white and color-infrared photographs over areas mapped as 7.5-minute quadrangles throughout the 48 conterminous States. Consistent acquisition parameters—an altitude of 40,000 ft (12,200 m) above mean terrain, a sun angle of at least 30 degrees above the horizon to minimize shadows, stereoscopic coverage, no cloud cover, and minimal haze—assured the quality and comparability of the data at a scale of 1:80,000 for black-and-white and 1:58,000 for color-infrared images. Data have been acquired when vegetation was dormant and during the growing season, and also with color-infrared film at higher spatial resolution (1:40,000, with each frame covering about 30 square miles). Individual trees and small areas of farmed fields are visible at this resolution.

Information on availability, coverage, products, and prices of NHAP/NAPP photographs can be obtained from the EROS Data Center, any one of the six National Cartographic Information Centers (NCIC), or the USDA's Agriculture Stabilization and Conservation Service (ASCS).

The SLAR program, administered by the USGS, is acquiring 1°×2° quadrangle radar images (scale 1:250,000) within the 48 conterminous States and Alaska. Radar acquisition parameters (depression angle and look direction) are adjusted in response to specific geologic characteristics and to specific goals of an investigation. Depression angles are chosen to emphasize subtle features, to minimize the area lost to shadowing, and to minimize an image distortion called layover, which is a characteristic of radar images of rugged terrain. Generally, a more acute angle is used over flat terrain and a less acute angle is used over mountainous terrain. Although rarely used because of their computational costs, image-rectification algorithms that reduce layover distortion are available. Look direction is selected to enhance interpretability based primarily on the predominant geologic structures. SLAR products, including strip images, mosaics, mosaic indexes, and computer-compatible tapes, are also available from the EROS Data Center.

This section provides a sampling of environmental issues and remote sensing activities within the U.S. Department of the Interior and the Environmental Protection Agency (EPA). Because the application of remote sensing data to environmental problems is a rapidly developing area of research, the examples given here do not completely depict the wide range of environmental remote sensing studies now underway. This is particularly true with respect to the use of remote sensing techniques to address global environmental change issues, which since the workshop meeting have become a major national research priority. The focus in this section is mainly on remote sensing techniques and applications that are currently operational; however, we also comment on several experimental applications of remote sensing data that may become important in the near future.

POLLUTION MONITORING

HAZARDOUS WASTES

Hazardous-waste remote sensing can be divided into large- and small-area categories. Large-area applications include regional and national surveys for point-source pollution or for potential toxic waste hazards. For example, the objective of the EPA's Spill Prevention Control Countermeasures program for river basins is to identify potential toxic waste hazards to watercourses. However, most hazardous-waste remote sensing focuses upon small-area investigations that are essentially analyses of site-specific problems. Within the EPA, small-area investigations are performed under the Resource Conservation and Recovery Act or under the Comprehensive Environmental Response, Compensation, and Liability Act. Such investigations are aimed at detecting and evaluating hazardous waste conditions at individual facilities or within areas of a few acres. Despite the smallness of these sites, monitoring with aerial photos (black-and-white, color, and color-infrared) and with airborne multispectral scanners can be conducted efficiently using techniques that are rapid and nonintrusive (fig. 12).

Stereoscopic photography is valued for descriptive analyses of existing and historical site conditions. Identifiable features of interest include ground disturbances (potential waste burial sites), waste types (liquids, solids, drums, and others), ground stains and stressed vegetation (and other waste-spill indicators), site activities (past and present), and waste storage and containment structures.

Figure 12. Color-infrared aerial photograph of a potential industrial pollution site. Photograph courtesy of the Environmental Protection Agency, Las Vegas, Nev., acquired December 18, 1980.

Aerial photography also provides the general characteristics of the terrain surrounding the site (topography, drainage, and cultural features).

The demands of small-area waste site analyses are driving the application of remote sensing toward higher spatial resolutions. The resolution of NHAP and of satellite images is generally not adequate for providing the required detail. Such studies could also benefit from higher spectral sensitivity to chemical anomalies and from the application of GIS technology for merging disparate data sets. Airborne laser fluorosensors and thermal scanners are expected to play an increasing role in small-area studies.

WATER QUALITY

The use of remote sensing in water-quality assessment has both a direct and an indirect component. Water quality may be measured directly in lakes, streams, coastal zones, and ocean environments through the combined use of remote sensing and water sampling. Water quality in surface waters and ground water may be estimated indirectly by categorizing land cover and drainage relationships and by using these data within models that predict water-quality parameters.

Both satellite and airborne multispectral scanning systems are used to map a variety of water- quality parameters (chlorophyll concentrations, Secchi depth, total suspended solids, total phosphorus, dissolved organic carbon, turbidity, salinity/conductivity, and others) in surface-water systems (fig. 13). In some cases, the accuracy approaches laboratory standards and, in most cases, spatial relationships are more reliably mapped by matching spectra over extended areas than by estimating trend surfaces from a limited number of samples. That is, multispectral data are calibrated by comparison with a representative set of water samples, and the results are easily extrapolated throughout the imaged area.

Airborne scanners provide a synoptic view that permits analyses of land cover and watersheds to identify local hazards such as nonpoint pollution, landfills, and unwise land use. However, because multispectral scanners "see" only to the light-penetration depth in water, risk assessments also require site-specific knowledge about circulation dynamics that generally can't be derived from remote sensing data alone. To augment remote sensing capabilities in this area, airborne laser fluorosensor systems are increasingly used to measure water quality (fig. 14). A laser illuminates a small volume of water, stimulating Raman emission from the water and fluorescence emission from the materials in the water. The ratio of the emissions can be calibrated to measure the light-attenuation coefficient and estimate the dissolved organic carbon, chlorophyll-a, blue-green algae, and oil films in lacustrine or marine environments. Advantages of the fluorosensor are that relatively few water samples are needed, the fluorescence characteristics of materials can be measured in the laboratory, and the system is more sensitive than passive systems. The disadvantage is that the system profiles rather than images, so that synoptic coverage requires many flight lines.

AIR QUALITY

Many air-quality regulations require air sampling with ground-based sensors at specific locations and times. Unfortunately, these data do not catch the dynamics of pollutant transport, especially in coastal areas or in areas of complex terrain where air-circulation models are poor. Passive imaging at visible to microwave wavelengths from satellites and airborne systems do show the horizontal distribution of airborne particulates from very strong point sources like major fires, power plant plumes, and dense urban smog. However, active airborne profiling systems such as Light Detection and Ranging (LIDAR) and millimeter-wave radar are far more sensitive to airborne particulates, and they yield the vertical as well as the horizontal distribution of pollutants (fig. 15). Polluting gases can be mapped with Differential Absorption LIDAR (DIAL). DIAL uses multiple lasers at wavelengths within and adjacent to gas-absorption bands to create profiles of vertical concentrations of pollutants.

The EPA currently flies a two-frequency LIDAR and is building an ultraviolet (UV)-range DIAL. The UV–DIAL will simultaneously measure ozone, sulfur dioxide, and particulate backscatter. The system will be used to enforce Federal air-quality regulations for ozone. Generally, new instruments employing DIAL technology will allow detection of most toxic gas emissions from waste dumps or spills.

EMERGENCY RESPONSE

Airborne remote sensing is a primary tool for emergency response to significant releases of contaminants. Most emergencies involve the spilling of pollutants into watercourses or onto the ground. If there is a threat to human life, the type of pollutant and its potential migration paths must be reliably and rapidly identified, and the information must be transmitted to emergency personnel. Aerial color photography is the primary emergency remote sensing tool because it is easily acquired and readily understood by emergency personnel. Photography's weaknesses are that it is insensitive to the type of pollutant, it cannot penetrate clouds or thick haze, and it requires daylight.

Imaging spectrometers and fluorosensors can be far better than film for identifying water or soil pollutants. However, the cost to hold dedicated aircraft and sensors on emergency standby has limited their development to the detection of classes of pollutants rather than to the identification of specific pollutants. The management of spill emergencies may spur a more rapid application of LIDAR, UV–DIAL, and millimeter-wave radar because few of the older

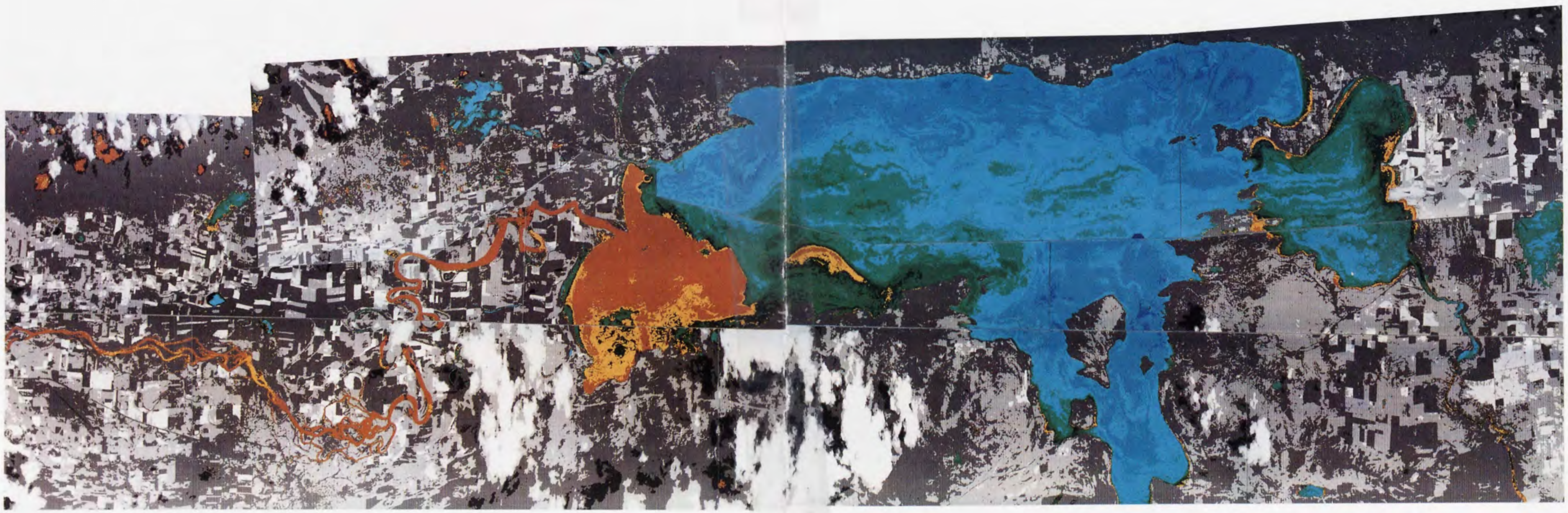

Figure 13. Multispectral airborne data used to estimate the average transparency of water to the Secchi depth. Montage courtesy of the Environmental Protection Agency, Las Vegas, Nev.

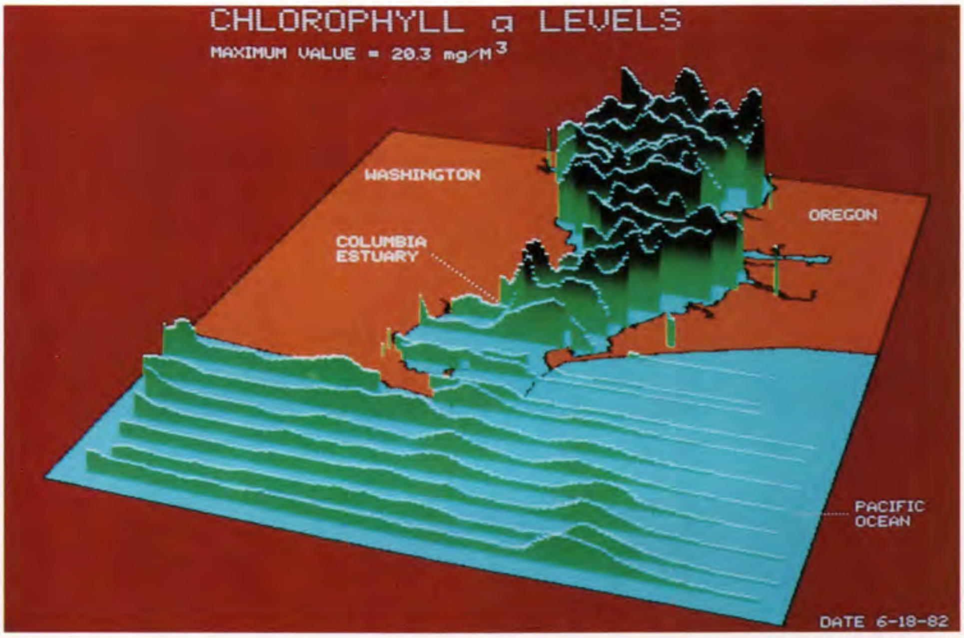

Figure 14. Laser fluorescence data from the Columbia River estuary, Washington, showing chlorophyll concentrations in the water. Courtesy of the Environmental Protection Agency, Las Vegas, Nev.

technologies are effective. The cost of maintaining airborne systems for emergencies might be avoided by strategically basing the sensors at various locations for deployment by locally available aircraft.

VEGETATION INVENTORY

Remote sensing has long been used to inventory and monitor vegetation. This includes ascertaining types of vegetation (or assemblages of species), their spatial extent and juxtaposition, their productivity, their general condition or health, and whether problem species (exotics, noxious weeds, and others) are present. Satellite data are used for general investigations of large areas, whereas airborne techniques are used for smaller areas and special investigations. Specifically, airborne remote sensing produces three categories of information: (1) vegetation typing, (2) vegetation condition, and (3) vegetation productivity.

VEGETATION TYPING

Vegetation typing refers to the identification and mapping of individual species (such as sugar maple) or commonly recognized groups of species (for example, beech-maple forests). Vegetation typing also includes identification or mapping of indicator species, exotic species, or troublesome plants (such as kudzu and tamarisk).

Airborne multispectral scanners, the primary sensors for vegetation typing, provide spatial resolutions of a few meters to several tens of meters depending upon the application. Airborne video, both natural color and false-color infrared, is starting to be used to produce inexpensive analog and digital panchromatic and multiband images. Airborne data are difficult to register to a map base because the perspective from airborne altitudes changes across most instantaneous fields-of-view, and because aircraft seldom maintain a uniform ground track or a constant attitude. Although the satellite Global Positioning System (GPS) will help in correcting some of these errors, airborne images of large areas are unlikely to have the geometric characteristics of satellite images.

Remote sensing is evolving toward the automated identification of vegetation species. Current methods used in vegetation differentiation by spectral characteristics, however, are generally limited to classification of certain hardwoods versus conifers, or certain classes of crops. Researchers are hopeful that a combination of high spectral resolution (imaging spectrometry) and sensitivity to plant physiology (multifrequency, quad-polarized radar) will provide the necessary discrimination to inventory and monitor vegetation resources.

VEGETATION CONDITION

Vegetation condition pertains to the general health of plants. Plants that are not healthy are said to be stressed. Among the various causes of plant stress are disease, injury from mechanical, insect, or chemical

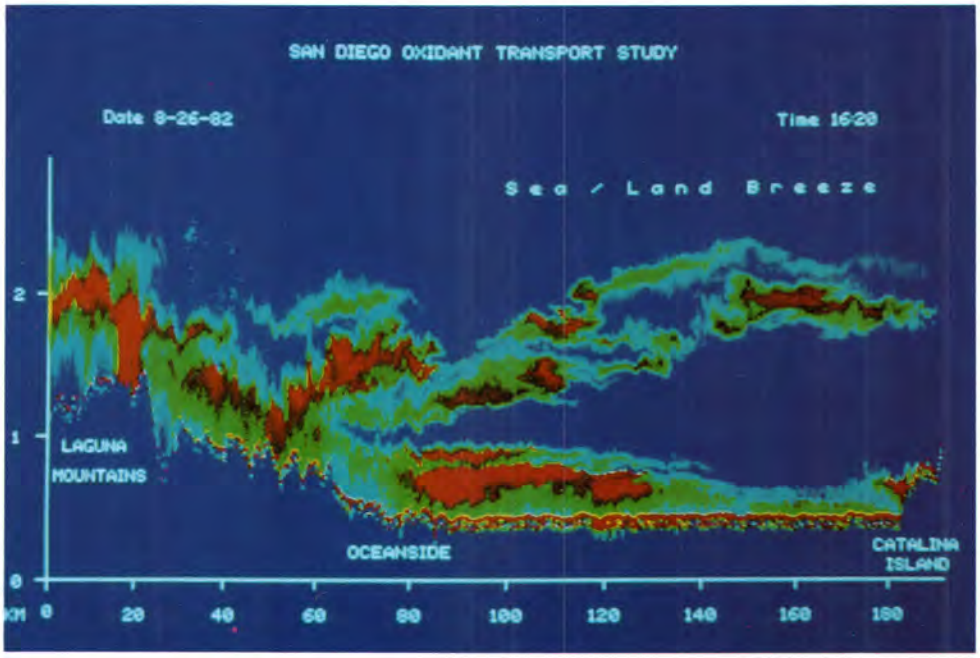

Figure 15. Distribution of airborne particulates in southern California (view looking south), as detected by an airborne LIDAR profiling system. Highest concentrations of pollutants are designated by the red areas. Courtesy of the Environmental Protection Agency, Las Vegas, Nev.

agents, and water-balance or nutritional deficiencies. Some plant stresses and stressors are specific to particular vegetation species and have characteristic physical manifestations (such as the ozone damage to white pines). Other stresses are more general and do not produce symptoms other than that a plant is unhealthy, dying, or dead.

Current airborne multispectral scanner techniques provide capabilities to recognize extreme plant stresses that eventually result in plant death. Application of remote sensing data to vegetation mapping of these highly stressful conditions, coupled with field studies, has become a powerful method for recognizing and sometimes ameliorating the effects of pollution, environmental change, insect infestation, and disease. Although there is some evidence that high-resolution airborne imaging spectrometers do detect subtle symptoms of plant stress or injury, reliable early detection will almost certainly require a combination of several sensors such as imaging spectrometers and multifrequency radar systems.

VEGETATION PRODUCTIVITY

Vegetation productivity is measured by the total biomass of an area. Productivity estimates are useful in fire-fuels modeling, ecosystem studies, wildlife-range-condition assessment, trend evaluations, and any other study where the primary vegetation productivity in an area is important. Airborne multispectral scanner data yield a "greenness index" that is empirically correlated to biomass. Airborne imaging spectrometry will allow refinements of the technique by permitting selections of spectral bands that better correlate with primary productivity.

MONITORING OF ECOTONE MODIFICATION

Airborne remote sensing is used to monitor temporal changes of ecotone regions—the transition zones between ecologic communities. Desertification and many coastal-zone processes are examples of ecotone modification. The study of desertification requires data on changes in sand and dust flux, surface temperature, soil moisture, biomass, and local and regional weather. Studies are often initiated well after the local process of desertification has begun. In such cases, the initial stages of the process are examined retrospectively using aerial photographs and Landsat MSS and TM data. In a few cases, high spatial and spectral resolution airborne multiband data (TIMS and AVIRIS) have been acquired early in the process. Airborne multifrequency, quad-polarized radar data also allow qualitative estimates of surface roughness and discrimination among vegetation types—attributes that vary during desertification.

Appropriate future airborne technologies might include GIS-registered land-cover images derived from solid-state, digital camera systems that more precisely and inexpensively detect and map desert encroachment. On the cutting edge of airborne technology, the new imaging spectrometers with high spectral resolution in the visible to near-infrared wavelengths have improved sensitivity to vegetation type when compared to the older generation of operational multispectral scanners. High spatial and spectral resolution thermal-scanner data (8–14 µm) might be used to obtain surface emissivities and temperatures that are needed in energy-balance models. Multifrequency radar should facilitate quantitative estimates of surface roughness and may also provide sensitive detection of subtle changes in vegetation type and soil moisture.

Remote sensing of coastal-zone processes includes the monitoring of erosion, lateral sediment drift, and vegetation-cover changes. The most commonly used technologies are airborne multispectral scanners and aerial photographs (black-and-white and color-infrared). The scanners also provide sediment chemistry, and both methods furnish point-in-time images for future comparisons. Existing technologies such as imaging spectroscopy or radar can provide greater sensitivity for monitoring soil chemistry, sediment load, and changes in soil moisture, but at higher cost.

As with desertification, digital land-cover maps produced with solid-state digital cameras or with high-resolution video systems may be a less expensive and more effective means of monitoring coastal-zone processes. Temporal changes in digital elevation models (DEM) derived from radar or laser scanning altimeters could be used to detect subtle changes in morphology.

LAND-USE ANALYSIS

Land-use analysis has been formalized according to the scale or resolution needed to achieve a specified classification level. There are four levels of classification:

Level[1]	Scale[1]	Pixel size	Example of system
I	<1:250,000	~80 m	Landsat MSS
II	<1:80,000	~30 m	Landsat TM
III	<1:20,000	~2 m	Aerial photography
IV	>1:20,000	<1 m	High-resolution aerial photography

[1]From Anderson and others (1976, p. 6)

Although some classifications can be automated (particularly for vegetation), land-use classification is generally labor intensive because the product requires an interpretation of land cover. That is, the product is prescriptive (land use) rather than descriptive (land cover). Improvements in land-use analysis are expected to come from research in artificial intelligence and spatial pattern recognition rather than from new sensor developments or from research in the physics of remote sensing processes.

Current capabilities typically center on skilled interpreters employing photointerpretive techniques and multiband image classification algorithms to achieve a resolution-dependent classification. These capabilities will grow with the incorporation of more spectral bands, other image data (such as radar), and better classification algorithms on more powerful computers. Sensing systems will increasingly move from aircraft to satellites as the spatial resolution of civilian satellite sensors improves. However, the fundamental improvement will come from the evolution and general availability of reference baselines and the general use of automated techniques for recognizing deviations from these baselines. Airborne remote sensing will probably play a diminishing role in this process.

FISH AND WILDLIFE MANAGEMENT

Remote sensing contributes to wildlife management through evaluations of habitat, population, and resource use. Although the primary focus is upon birds, mammals, and freshwater fishes, the techniques apply to other animals as well.

HABITAT

A fish or wildlife habitat is an integrated summation of several environmental components with vegetation and water as the primary elements. The distribution, condition, and types of vegetation are critical to evaluating habitat because vegetation provides forage and cover (escape, thermal, or reproductive). A similar set of water-related attributes determines the habitat for fish. Satellite data are used for general habitat assessments over large areas, whereas aerial photography is used for detailed investigations (fig. 16). The technologies used for vegetation remote sensing are the same regardless of the habitats being evaluated.

The distribution, depth, clarity, and trophic level of waters are being determined by airborne multispectral scanning techniques. Multiband airborne video systems appear to have many of the beneficial attributes of multispectral scanning but should provide data at lower cost. Thermal-infrared scanners have been used in arid environments to detect small seeps or springs, and longer wavelength radar has been used to detect standing water under forest canopies.

POPULATION

Species populations can be determined by remote sensing if the animal size matches the sensor's resolution and if the animals spend some of their time in the open. Aerial photography and airborne video systems are effective reconnaissance or population-sampling tools for waterfowl and ungulates. Thermal-infrared scanners have been used with limited success to count large mammals. Difficulties occur because of inadequate spatial resolution of thermal-infrared scanners, poor thermal contrast between a well-insulated

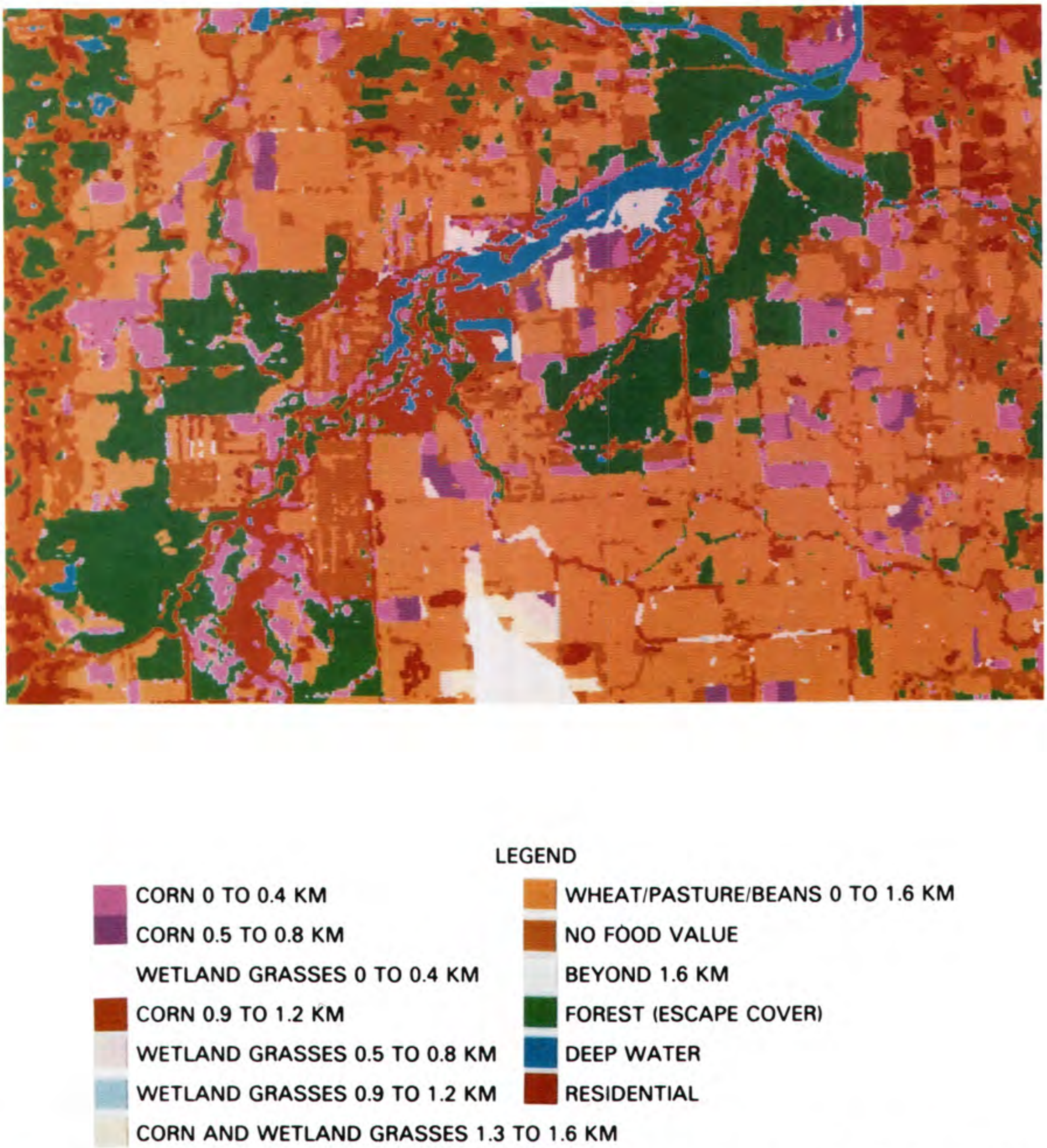

Figure 16. Map showing potential food availability in wildlife foraging areas based on a classification of airborne multispectral data. Numbers in legend denote distances to forest escape cover. Courtesy of the U.S. Corps of Engineers, Detroit, Mich.

animal and its environment, and because the technique cannot distinguish among species (such as deer confused with antelope, and cattle confused with elk).

RESOURCE USE

The resources used by wildlife are difficult to measure with airborne remote sensing. Obvious evidence of wildlife use generally implies overuse. Game trails, overgrazing and trampling around riparian areas and watering holes, and browse lines in deer yards are examples of overuse. Nadir and oblique aerial photography and airborne video are the appropriate technologies for this application because of their low cost and relative effectiveness. Although current use favors aerial photography, airborne video will become more popular as wildlife managers become accustomed to the technology.

FIRE MANAGEMENT

Wildfires blacken thousands of acres of public and private lands annually and cause enormous losses of property, timber, rangeland resources, watershed resources, and wildlife habitat. Federal land-management agencies (Bureau of Land Management, U.S. Department of Agriculture, U.S. Forest Service, National Park Service, and others) have congressionally mandated fire-management programs. State and local government agencies also participate in fire detection and suppression. Wildfire management falls into four general categories: (1) fire-fuels mapping and presuppression planning; (2) detection, management and suppression; (3) damage assessment; and (4) rehabilitation planning. Fire management is a complex process involving a wide variety of correlative data, sophisticated equipment, extensive communications, and highly trained professionals. Remote sensing plays a vital role in all four categories because wildfires frequently occur in remote and inaccessible areas.

FIRE-FUELS MAPPING

Landsat MSS and TM data along with AVHRR data are used operationally to classify and map fire fuels in large areas in the Western United States, Alaska, and Canada. Higher resolution aerial photographs are used to select training areas for automated classification of satellite data and to check the results of fire-fuels mapping in ecologically similar areas. Whereas low- and medium-resolution satellite data will continue to be the appropriate technology for fire-fuels mapping of extensive forests and rangelands, airborne imaging spectrometers will increasingly be used in combination with the satellite data to improve fire-fuels classification.

DETECTION AND MAPPING

Airborne thermal-infrared scanners operating in two atmospheric windows (3–5 μm and 8–14 μm) are used operationally to detect fire hot spots and to map fire locations at night or through smoke and haze. The Boise Interagency Fire Center in Idaho coordinates the national use of these airborne scanning systems.

NASA used its research fire-detection and mapping system in a U–2 reconnaissance aircraft over the Pacific Northwest and California during the summer of 1987 and has flown TIMS in a Learjet over California for fire-detection tests. Similarly, a 3 mm imaging radiometer designed for small aircraft has produced high-resolution images of the ground through smoke, dust, and clouds that were optically opaque to visible and infrared sensors. Such technology might locate fires that are obscured by smoke or low clouds.

Future fire-detection and mapping systems for the conterminous United States will be airborne rather than spaceborne because of the need for special sensors and for immediate and repeated coverage. Such systems are likely to consist of thermal-infrared linear-array detectors operating in the two atmospheric windows, a GPS receiver for location information, an on-board data processor, and a satellite communications link to a ground-display subsystem. For remote regions of Alaska, Canada, and Mexico, a cost-effective system might combine TM band 6, the 3.8 μm band of AVHRR, and supplemental airborne systems. Similar combinations of satellite and airborne systems might be used in third-world countries to monitor slash-and-burn agricultural practices. The effects of these practices upon climate and upon the economic well-being of these countries should justify the cost.

DAMAGE ASSESSMENT

After a fire occurs on public lands, information is needed on the areal extent and severity of damage. Burned areas have been mapped with satellite data. Aerial reconnaissance and aerial photography are frequently used to assess fire damage, and airborne video cameras have recently been tested in Montana for postfire assessment. Enhanced video systems will be increasingly employed where time is a critical factor. The cost of current high-quality airborne radar may be justified for remote surveys where poor weather or atmospheric conditions prevent use of other sensors. The new generation of digitally correlated, multifrequency, quad-polarized radar will yield more complete damage assessments than are possible with older radar systems. It is unclear whether the improvement in fire damage assessment warrants the higher cost of the new radar.

Federal and State land-management agencies carry out reseeding and reforestation activities in areas affected by fires. Satellite and airborne data are used to map the burned areas and to prepare rehabilitation plans. In some cases, aerial photographs are used to monitor rehabilitation progress. In the future, image data in the visible and near-infrared could be used in rehabilitation activities if they are readily available at reasonable cost.

PHYSIOGRAPHIC BASELINE DETERMINATION

Environmental studies very often require baseline information about topography, geography, land cover, and land use. Most of the data for this physiographic baseline are acquired with airborne photography because it provides high spatial resolution data in a familiar format at reasonable cost. Radar is being used in an experimental mode to supplement these data.

Airborne laser profilers coupled with precise navigation systems produce terrain profiles that are accurate to a few centimeters. These systems are expensive to develop and operate. GPS interferometer technology will facilitate the use of far simpler and less costly navigation systems. These navigators, combined with laser or millimeter-wave terrain scanners, will result in more robust and less costly centimeter-accuracy topographic mapping systems.

Digitally correlated synthetic-aperture radar data can be processed to yield an elevation model of the terrain. Although these models are accurate to only a few meters, they are appropriate for reconnaissance surveys after an explosive volcanic event or a major earthquake. Current processing is slow, but the time required to produce terrain models could be shortened if the capability is found to be of value.

MONITORING GLOBAL CLIMATE

The question of variability of global climate lies at the center of a new earth-science discipline called Earth System Science. The premise of Earth System Science is that the Earth functions as an evolving, integrated system whose dynamics can be understood only in a global and interdisciplinary context. Human activity can affect Earth System dynamics. Increased stratospheric carbon dioxide and chlorofluorocarbons, tropical deforestation, and acid rain are examples of anthropogenic perturbations to Earth systems. The consequences of such perturbations are poorly understood because the systems' natural dynamics are poorly understood.

The central theme of Earth System Science appears in the following report by the Earth System Sciences Committee (1986):

> A fundamental aspect of Earth System Science * * * is the emphasis on an integrated view of the interactions of the lithosphere, the physical climate system (including the atmosphere, oceans, and land surfaces), and the biosphere (coupled to the other components through the biogeochemical cycles). These systems participate individually and collectively in global change on all timescales. Once change is introduced, it can propagate through the Earth System. Because of the coupling among the Earth's components, change in one component can affect the others. Because of the nonlinearity of the system, change at one timescale can propagate into other temporal ranges.
>
> Hence the central approach of Earth System Science is to divide the study of Earth processes by timescale, rather than by discipline. This approach incorporates specifically the interactions among the components, as required by an integrated and systemic view of the Earth. Accordingly, we must now view the Earth as a dynamical system, described by a collection of variables that specify its state and the associated rules for inferring how a given state will evolve. Through this central approach, we thus seek to (1) describe, (2) understand, (3) simulate, and (4) predict (perhaps in a statistical sense) the past and future evolution of the Earth on a planetary scale.

Satellite remote sensing permits global descriptions of the Earth at time scales as short as days or hours. Airborne remote sensing is important for calibrating satellite techniques and for providing intense coverage with special instruments as part of large regional projects, such as the Global Atmospheric Research Program's (GARP) Atlantic Tropical Experiment (GATE), Polar Experiment (POLEX), and Arctic Ice Dynamics Joint Experiment (AIDJEX). Airborne systems also provide relatively inexpensive test platforms for sensor and technique development.

Examples of global environmental phenomena that concern the U.S. Department of the Interior include world volcanic activity, sea-ice cover and dynamics, temporal variations in the regional hydrologic cycle, temporal variations in sea level, changes in the distribution of permafrost, trends in annual snowfall, temporal variations in the Earth's ice mass, and ecotone boundary migration. Except for volcanic activity (see section on volcanic hazards), these phenomena generally concern the distribution, state, and dynamics of water. The distribution and state of water is most readily mapped (particularly where partial vegetation cover is present) with microwave and thermal-infrared techniques. Although the distribution of water often determines ecotone boundaries, repetitive and frequent vegetation maps are probably more useful for detecting boundary migration than are moisture maps. Microwave and thermal-infrared satellite systems currently have relatively low spatial resolution and thus do not provide the type of data necessary for observing the fine structure in boundary areas that are associated with global change.

Current airborne capabilities include sea-ice mapping (cover and type) with SLAR or with imaging microwave radiometry, sea-ice thickness mapping with airborne induction techniques, relative soil-moisture mapping with radar scatterometry and radar and thermal-infrared radiometry, and ice-sheet depth and structure profiling with short-pulse radar (HF, VHF, and UHF wavelengths). Relatively few SLAR, scatterometer, radiometer, and short-pulse radar systems exist. Although NASA, the USGS, the U.S. Department of Defense, and at least one commercial operator collect SLAR data, the operations are expensive and the image products are of variable quality. Scatterometry is becoming commercially available from one commercial source at a line-mile cost comparable to aeromagnetics ($30–$50 per line-mile). Use of airborne microwave radiometer systems that are developed as part of government projects can sometimes be negotiated with project managers or investigators, but access is clearly limited and uncertain. Helicopter-borne, short-pulse radar is becoming commercially available.

Efforts to expand remote sensing of the hydrosphere are focused primarily upon the use of satellites because they provide coverage that is broad and generally frequent. The single new technology that will most enhance airborne remote sensing of sea-ice, glaciers, and soil moisture is GPS. With GPS, profiling scatterometers and radiometers will be preferable to imaging radar and radiometers for many applications because profiling sensors cost less, have better calibration, and view with a constant geometry. GPS will provide worldwide, autonomous guidance over featureless or changing terrain (such as sea-ice and glaciers) and will permit accurate line recovery for postflight image construction or data registration.

Research with advanced, airborne microwave systems may lead to quantitative soil-moisture and snowpack water-equivalent mapping from satellites. The problems are formidable because weak bonding of water in clay results in dielectric properties of soil that are dependent upon soil type as well as upon water content, and also because metamorphosis and partial melting within a snowpack greatly alter snow scattering characteristics. However, the new generation of calibrated multifrequency radar, scatterometers, and radiometers, and advances in scattering theory provide encouragement for the future.

HAZARDS

Working Group: R. Lyon and T. Ridley (*Cochairmen*), P. Carrara, A. Kahle, D. Peters, R. Vincent

Geologic hazards are natural phenomena that threaten property or life. Airborne remote sensing methods, because of their rapid deployment, synoptic view, and high spatial resolution, have the potential to delineate and monitor phenomena related to geologic hazards. Conversely, Landsat data are much less useful because of the 18-day-coverage repetition rate and lower resolution. To date, virtually all operational remote sensing for hazards is done by aerial photography. This reflects the need for rapid mobilization during crises and a general usefulness and familiarity with the data. Advances in remote sensing detector technology and increasing use of digital image processing will gradually change this approach as new acquisition systems become more available. In this section, we discuss the application of remote sensing methods to landslides, flooding, volcanic hazards, faults and earthquakes, subsurface coal fires, in-mine ground-control hazards, and subsidence.

Any study of geologic hazards by airborne remote sensing consists of two parts: (1) initial recognition of a hazardous feature (such as a landslide), and (2) subsequent monitoring of this feature. High spatial resolution (1–2 m) is essential for the evaluation of geologic hazards, but it is not yet fully addressed by most nonphotographic remote sensing. In practice, airborne remote sensing may be the easiest and most effective means to monitor geologic hazards in remote areas. At times when surface travel to a site is impractical or dangerous it may be the only method. Although the potential for employing remote sensing methods in identification and monitoring of geologic hazards is significant, application beyond photography to date has been minimal. The following sections describe proven or currently feasible methods and future applications that might be possible based on extensions of present technology.

DEMONSTRATED REMOTE SENSING CAPABILITIES IN GEOLOGIC HAZARD MONITORING

Aerial photography is the most widely applied remote sensing method and is used to document the extent and surface features of geologic hazards. Black-and-white stereo, low-sun-angle, and color and color-infrared photographs are used independently or in combination to evaluate hazard areas and to provide a base line for measuring change. Surface features such as scarps, hummocky terrain, scarred valleys, advancing flow fronts, lineaments, and vegetation distribution can readily be identified on aerial photographs. Low-sun-angle photos show subtle topography that is not always obvious from ground observations or conventional aerial photos, and these data are particularly useful in areas of unstable ground. Linear drainage patterns (and their disruption) may be surface indicators of faulting, structural control, or mass-movement phenomena. Not all structural features (particularly fault planes) are expressed topographically, but they may in some cases be expressed as temperature and reflectance changes in remote sensing data due to enhanced or reduced plant growth because of preferred water migration paths.

LANDSLIDES

Landslides are the downward and outward movements of slope-forming materials due to near-surface failure, commonly triggered by fluid lubrication of shear surfaces and earthquakes. Landslide deposits can consist of incoherent jumbled masses (debris slides) or largely intact blocks (rock-block slides). Preconditions for potential landslides include steep slopes where internal frictional forces are only slightly greater than gravitational forces. If these slopes become saturated with rain, reducing the internal friction, a critical state of instability is reached. Some type of vibration (such as an earthquake or explosion) can initiate movement, or the slope may slide without any overt trigger event.

Landslides may indirectly produce other hazards, such as releasing an avalanche-dammed lake. Although landslides are inevitable, it may be possible to predict their occurrence and reduce the threat by monitoring indicative precursor conditions. These include rainfall, soil moisture, evidence of previous small landslides, and steep erosional surfaces. Largely photographic remote sensing methods are currently used to identify and monitor areas prone to landslides. Airborne multispectral-reflectance surveys could be used to detect vegetation differences using color-infrared ratio composites (CIR) and to delineate clayey sediments or other ductile materials like gypsum that could provide potential slip surfaces in inclined sedimentary rock. Thermal-scanner surveys can be used to detect patterns in near-surface ice and snow that may cause avalanches, lithologic boundaries of clay-rich layers in sediments, water seepage along bedding planes that commonly are slip surfaces for landslides, and moisture build-up that may be a precursor to landsliding. Although conventional radar is used in monitoring topographic variations resulting from landsliding, radar data do not yet have enough spatial resolution (<1 m) to be applied to the monitoring of landslides.

However, a number of techniques do exist for acquiring high-spatial-resolution topographic information from airborne systems. These include laser profilers, stereo photography, and digital radar. In addition, multifrequency radar can be used to discriminate ground-surface roughness and moisture differences in unstable areas. Both high-resolution topography and surface texture might provide indications of incipient movement.

FLOODING

A destructive flood can occur when a stream fills its channel and overflows onto adjacent land. Most streams on average experience discharges in excess of channel capacity about two or three times a year. Although most floods are small, less frequent floods can discharge tremendous amounts of water (the 1976 Big Thompson flood in Colorado exceeded the 100-year flood by a factor of three). Flooding can occur very quickly from a powerful, slow-moving thunderstorm, can build up slowly and predictably depending on the rate and amount of snow melt, or may result from the rupture of a dam or other entrapment. In mountainous terrain, a flash flood can be particularly dangerous because of the speed and violence with which it occurs. It is often necessary to determine the extent of flooding in order to take remedial action. Under conditions of continuous cloud cover, radar can be used to acquire data to assess the extent of flooding. Although these data are not generally available quickly from commercial sources, military systems are sometimes accessible in emergencies. Photographic remote sensing provides a means of rapidly mapping the land-water interface and monitoring changes. It is specifically useful when digitally coregistered to maps to determine the exact location and extent of flooded areas and to monitor changes in riverbank and shoreline positions before and after flooding. Such data provide quantitative information on the scope of the hazard and its impact on a community. This can be important for insurance purposes, future mitigation efforts, and long-range land-use planning.

VOLCANIC HAZARDS

Volcanoes can erupt passively or explode violently depending on the viscosity of the magma and the abundance and condition of contained gases. The synoptic views provided by remote sensing data can have an important role in detecting the extent and progress of volcanic eruptions. Conventional photography can be used to document the various eruptive phases and the extent of damage to surrounding properties. High-resolution stereo photography can also be employed to provide baseline topographic control, to estimate mass removal, and to predict future flow directions. Thermal-infrared surveys are useful for mapping the extent of hot material, for detecting changes at night, and for finding "hot spots" (usually fissures) from which hot gases are emitted. Remote sensing also provides useful information about lithology and structure in volcanic hazard areas (see the Geologic Mapping section). Multispectral-reflectance and thermal-infrared data have shown that differences among flow units can be detected, which suggests that this is a promising area for future research. In some circumstances, pre-eruptive conditions such as ground tilting and swelling could be monitored by laser profiling. The extent of an erupted ash layer can be estimated using photography, nighttime thermal-infrared images or radar images through cloud cover, and in some situations it may be possible to estimate ash thickness using day/night thermal-infrared data.

FAULTS AND EARTHQUAKES

Earthquakes are the sudden motion of the ground caused by the abrupt release of slowly accumulated stress. They occur in the Earth's upper mantle and crust, with faults at the surface often marking earthquake zones. Recognizing and monitoring the changes in a fault zone can lead to an improved understanding of earthquake mechanisms and a possible method of prediction of their occurrence.

A wide variety of remote sensing methods can contribute to earthquake studies. For instance, radar measurements can detect changes in elevation, roughness, and moisture content and, hence, are valuable in detecting faults. Both radar and thermal-infrared devices are extremely sensitive to the moisture content of the soil and can be used to indicate differences in soil type across fault boundaries, which may not be recognizable from ground observations. Thermal-infrared scanners have also been used to detect faults expressed by the juxtaposition of lithologic units with differing thermal properties. Other associated features that could be observed include sag ponds, sand blowouts, and other surface phenomena associated with ground movement.

Currently operational methods of remote sensing such as three-dimensional, high-resolution digital terrain maps, digital radar, multispectral scanners (reflectance and thermal), and laser profilers have the potential to provide valuable topographic, structural, and lithologic information for identifying faults and for monitoring changes associated with them. To date, however, little has been done in this area.

COAL FIRES

Coal fires can be either natural or man-induced. For example, large underground fires in the Powder River Basin of Wyoming, presumably caused by lightning strikes, have been burning for thousands of years. However, fires that are of most concern generally are related to mining activities. These fires can be in coal seams or the spoil piles left from older mining operations. In all cases, they produce noxious and deadly gases such as carbon monoxide that are harmful to those living nearby. Mine and seam fires also can cause subsidence due to collapse of the overlying rock as the coal is consumed. In any event, the overlying surface can be rendered uninhabitable, and vegetation may be killed by the heat or by escaping gases.

Coal fires are identifiable by remote sensing in the areas where the ground is recognizably warmer than the ambient temperature or (more usually) where hot gases escape to the surface through fissures and joints. Airborne thermal-infrared scanners have been used to monitor and in some instances identify these conditions. Additional monitoring can be accomplished by using multispectral scanners to detect stressed or dead vegetation resulting from the high heat flow and associated gases.

IN-MINE GROUND-CONTROL HAZARDS

Because mining involves creating openings in a rock mass that has preexisting fractures and stresses, instability can occur. Problems caused by stresses and instabilities are referred to as "ground-control hazards" and can take the form of roof falls, water inflows, pit-wall collapses, areas of rapid closure of openings, or "rock bursts"—catastrophic bursting of rock around openings. Both surface and underground mines have ground-control problems, although the type and extent of the problems will vary with depth of the mine, type of material mined, and the mining method. Such hazards can have a major effect on the productivity of the mine and the safety of the miners.

Ground-control hazards related to fracturing in the rock mass, and areas prone to these hazards can often be identified through lineament analysis of remote sensing data of the overlying ground surface. The data used include photographs and images from multispectral scanners (reflective and thermal) and radar imaging systems. Once the relationship between lineaments and their surrounding geology is understood, the data can be applied as a planning tool for future mining operations. Different methods provide different data: reflective multispectral systems provide the highest spatial resolution (a few meters), allowing geomorphic aspects and vegetation differences that may be associated with fracture-controlled porosity to be detected; thermal infrared is very sensitive to subtle soil-moisture differences that might indicate fractures; and radar detects surface-roughness characteristics that might also relate to fracture controls.

SUBSIDENCE

Subsidence can be hazardous where human activity and habitation coincide with subsidence-prone geologic terranes and areas of underground mining. Natural subsidence includes formation of sinks and cavities in soluble rocks such as limestone and localized compaction of weak sediments such as regions of sand and loess found in the Central United States. Subsidence-prone areas are commonly of the same extent as the geological units that bear these properties. The areas are characterized by closed depressions that may contain water.

Subsidence related to underground mining is most common in areas that contain coal deposits, but it can occur over any mine. Old mines pose a special problem in that their extent may not be known. However, it is generally safe to assume that mines that are no longer active or have been abandoned for more than 20 years have begun to subside. Mine subsidence patterns follow the layout of the mine workings, so that ore or coal left in place in the mine causes high spots bounded by subsided areas that may follow the interconnected mine openings. Such depressions are commonly dry because of the subsurface drainage of the features.

Subsidence can cause damage to manmade structures and, consequently, pose danger to humans. It is commonly a slow process, with the sink or depression gradually becoming deeper as material falls into the underlying voids. However, movement can sometimes be rapid and catastrophic, resulting in caverns opening to the surface or the formation of new or larger and deeper sinks. Regardless of the tempo of ground movement, structures constructed in areas undergoing subsidence will be pulled apart or will collapse into sinkholes.

Subsidence-prone areas are often very distinct on conventional photography, but more subtle expression can be identifiable using airborne radar and profilers. Thermal-infrared scanners provide useful information on lithologic differences and water content of soils in subsidence-prone areas. Changes in surface roughness and texture, and vegetation variations detectable by multispectral scanners and radar can also indicate increased fracturing associated with the subsidence.

FUTURE REMOTE SENSING APPLICATIONS IN GEOLOGIC HAZARD DETECTION

Several remote sensing methods that are presently in developmental stages appear to have great potential for application to geologic hazards. These instruments all have increased spatial ($\leq$10 m) and spectral (~10 nm in the 0.4–2.5 μm range) resolution and will greatly improve the monitoring of textural, mineralogic, and moisture changes associated with geologic hazards.

Digital terrain maps produced by solid-state digital cameras are a direct extension of current technology using stereo photography. They can provide accurate documentation of geologic hazards that is compatible with GIS and, in known hazardous areas, can also provide a base line for retrospective viewing. These maps can also be used to estimate the extent of ground mass movement, the areal distribution of hazardous conditions, and possible flow paths for movement of materials.

Finally, multifrequency radar and thermal-infrared measurements might be useful in hazard studies for detecting moisture changes and surface elevation changes that could be precursors to landslides and subsidence.

WATER RESOURCES

Working Group: K. Lee and H. Lins (*Cochairmen*), R. Clark, A. England, T. Mace, M. Nyquist, C. Stanich, J. Turner

For more than three decades, hydrologists and water-resource specialists have been applying remote sensing techniques to studies of water resources and problems in water science. The experience has been characterized by numerous contrasts, most of which are directly related to the nature of water itself. For example, the absorption and reflectance of water in various regions of the electromagnetic spectrum make liquid water, snow, and ice easily detectable from airborne and spaceborne platforms. In contrast, other aspects of water such as its presence in soils and aquifers and its continual phase changes are not amenable to direct remote observation. As a result, the uses made of remote sensing in water-resource activities can be organized generally into two groups: those based simply on direct visual observation of a water body (in liquid and solid states) and those based on interpretation of surface features associated with subsurface water. The former makes extensive use of visible and near-infrared photography and images, whereas the latter generally utilizes data collected in the nonvisible regions of the spectrum.

Most current remote sensing capabilities in water-resource applications involve the use of photography and images. These include delineating the extent of water bodies (including snow and ice); measuring ice concentration; assessing turbidity; floodplain mapping; identifying indirect indicators of groundwater (such as surficial geologic and geomorphologic features and vegetation); and identifying indicators of evapotranspiration (such as vegetation and land use). An extensive literature detailing these capabilities has developed, but because most of this work has become routine it is not reiterated here. Rather, the focus of this section is on those aspects of water resources where the applications of remote sensing are less established or defined, and which exploit existing and evolving airborne sensors. Topically, the emphasis is on special aspects of snow and ice, soil moisture, evapotranspiration, and ground water.

DEMONSTRATED REMOTE SENSING CAPABILITIES IN WATER-RESOURCE STUDIES

SNOW AND ICE

Snow- and most ice-covered areas have strong reflectance characteristics in the visible and near-infrared region of the spectrum. Landsat MSS images and conventional aerial photographs have been very useful in mapping the extent of snow-covered areas and areas covered by most forms of ice. Certain ice types, however, exhibit low reflectance in the visible and near-infrared regions, thus making ice-cover mapping somewhat less reliable. Moreover, several other general disadvantages are associated with using visible and near-infrared images for snow and ice work. First, such observations provide information only on surface conditions; equally important details regarding subsurface properties are not detectable. Second, clouds are frequently present over snow and ice regions, partially or totally obscuring the surface. Third, visible and near-infrared observations are functionally dependent upon solar reflectance, thereby restricting data collection to daytime sensing and during the daylight seasons in polar regions.

From a hydrologic perspective, interest in snow is primarily directed toward the estimation of meltwater quantity, which requires information on both the areal extent of snow cover and the snow's water equivalent. Although nearly all sensors provide some information on the areal extent of snow, visible and near-infrared photography and images are the most extensively used. Snow water equivalent, on the other hand, can only be measured in the nonvisible wavelengths. The most reliable method of determining the water equivalent of snow is currently being used operationally by the National Weather Service's Office of Hydrology and involves measuring surface gamma-radiation emission using a sensor aboard a low-flying aircraft. Natural terrestrial gamma radiation is emitted from potassium, uranium, and thorium radioisotopes in the upper one-half meter of soil. During the snow-free season, the gamma-ray emission can be measured from an aircraft flying 150 m above the ground. The flight is then repeated during the snow-covered season with the radiation signal received at the sensor attenuated by the water mass in the snow cover. Thus, the difference between measurements recorded over bare and snow-covered ground can be used to calculate a mean areal snow water equivalent value with a root mean square error of less than 1 cm. The technique measures the attenuation of the radiation signal resulting entirely from the intervening water mass, but it provides no information about snow depth.

SOIL MOISTURE

As with snow, the variation of natural terrestrial gamma radiation, which is strongly attenuated by water, can be used to measure soil moisture. This remote sensing approach is the only one that has been developed sufficiently for operational application. Because most of the gamma radiation that can be measured over the ground originates in the top one-half meter, the attenuation of the radiation is dominantly affected by soil-moisture changes in the top 20–30 cm of soil. This technique does not yield absolute values of soil-moisture content and requires that in-place measurements of soil moisture be made during overflights. Vegetation does not affect the technique's accuracy, making it possible to be used even in forested areas. Soil-moisture measurement errors associated with this method average ±5 percent, making it the most accurate of all remote sensing methods used for this purpose.

There are, however, distinct limitations and constraints associated with the use of this technique that must be considered. For example, the atmosphere is a strong attenuator of gamma radiation and the measurements must be made from aircraft flying only between 50 and 150 m above the ground. Moreover, the sensor, a gamma-radiation spectrometer, is expensive and requires extensive calibration. Given the large potential spatial variability of natural terrestrial gamma radiation, successive measurements of a particular area must be taken along precise flight lines. Measurements are not possible over saturated soils because of the strong water attenuation. Also, rapid changes in the concentration of radon gas in the air can produce serious measurement errors if the instrument is not carefully calibrated.

GROUND WATER

Thermal-infrared images are effective for locating areas of ground-water discharge. Ground water has a nearly constant temperature, whereas the land surface varies both diurnally and seasonally, and thermal contrasts of several degrees occur. Current infrared scanners can detect differences of about one tenth of a degree Celsius. Where ground water flows into open-water bodies, springs discharging as little as a few gallons per minute can be mapped if their temperatures differ by a few tens of degrees, and large springs require only a few degrees difference. Diffuse shoreline seepage can be mapped under calm conditions. Where ground water discharges at the ground surface, high soil moisture occurs. This causes an increase in evaporative cooling and in thermal inertia, which produces cool anomalies in daytime thermal-infrared images.

Infrared photographs and scanner images (0.7–1.1 µm) readily distinguish phreatophytes (plants that tap the water table) from xerophytes (plants that subsist on moisture in the soil zone). Interpretation of infrared photos and images of arid and semiarid regions determines areas of ground-water discharge by transpiration. Where the plants can be identified in the images, supplemental information can be derived on depth to the water table and on water quality; for example, in the Western United States, willow stands indicate potable water less than 5 m deep.

Where ground water is controlled by fractures in low-permeability rocks, mapping linear structural elements on images and photos from airborne sensors is effective in locating wells with enhanced yields. This technique is applicable in both arid and humid regions using photographs and images acquired from spacecraft and aircraft.

EXTENDED REMOTE SENSING CAPABILITIES IN WATER-RESOURCE STUDIES

SNOW AND ICE

Emittance and backscattering of microwave radiation are affected by almost all snow parameters, which complicates the measurement of the most needed parameters including areal extent, amount of free water, and water equivalent. However, developmental work indicates that microwave remotely sensed data can be used to at least infer these conditions. The polarization factor derived from the 10.7-GHz-brightness temperature may also provide an adequate index of underlying frozen soil conditions. Passive microwave satellite data from the Nimbus 5 and 6 electrically scanning microwave radiometers (ESMR) and the Nimbus 7 scanning multichannel microwave radiometer (SMMR) have been used to determine snow properties over large areas at a resolution of tens of kilometers. Study results indicate that snow boundaries can be defined at 37 GHz and 18 GHz frequencies because of a sharp decrease in brightness temperature when going from a dry to a snow-covered surface. The onset of snowmelt can be detected at both 37 GHz and 18 GHz because of the significant decrease in volume scattering that occurs in the presence of free water.

The estimation of the water equivalent of snow is more complex. For dry snow over bare soil or short-vegetation areas, the brightness temperatures of the 37 GHz data decrease inversely with snow depth in response to the stronger scattering effect of deeper snow. The sensitivity to snow depth is not as great at 18 GHz, however. A new microwave technique offers improved water equivalent estimation capabilities, especially for extrapolating estimates over broad geographical regions. The broad spatial capability is significant because the operational gamma-radiation technique, although accurate, has a very narrow footprint, and broad geographical coverage is impractical. The new method couples airborne passive microwave measurements of snow over a broad spatial domain with a series of in-place microwave measurements obtained with a recently developed device called the Snow-Ice Dielectrics System (SIDS). The airborne and in-place sensors both operate at four matched frequencies, and the detailed dielectric properties (which can be related to the water content of the snow) measured with SIDS can be extrapolated to the larger area of airborne microwave coverage.

Looking specifically at ice, recent radar studies on Alaskan lakes indicate that discrimination is possible between lakes frozen completely to the bottom versus lakes with fresh water beneath the ice, thus providing additional information on lake depth. The measurement of lake-ice thickness was accomplished using a short-pulse airborne radar system. This same technology has also been used to map alpine-glacier and polar-ice thickness to a depth of 3,000 m. Data from such radar systems also make possible the estimation of ice volumetric changes. Airborne passive microwave radiometers have been used to detect the vertical variations in snow, from ice at the bottom layer to recent snow at the top.

SOIL MOISTURE

Airborne remote sensing in the thermal-infrared and microwave regions of the spectrum offers some potential for characterizing soil-moisture conditions, although these capabilities have been slow to evolve and have many problems. Thermal-infrared sensing can be used for measuring thermal inertia, which is strongly dependent on soil porosity and moisture content. Day and night flights are required to measure the diurnal amplitude of the ground temperature. Accurate estimates of the thermal inertia require detailed knowledge of the energy fluxes at and near the ground surface.

Current procedures indicate that soil moisture in the top 5 cm can be determined, although studies under optimal atmospheric conditions over bare soil have found that estimation errors in the top 2 cm average about 35 percent. In vegetated areas, the diurnal variations of soil temperature can be detected only when the vegetation is low and homogeneous. In practice, only areas under cultivation are suitable for estimating soil moisture using this temperature-based method. Estimates cannot be obtained for forested areas or during times of cloud cover.

Another technique undergoing developmental work involves passive microwave radiometry. The microwave brightness temperature of bare soil is determined primarily by the dielectric properties of the soil and the temperature and roughness of its surface. Soil dielectric properties are influenced strongly by moisture content. Airborne and spaceborne studies have shown an inverse relationship between brightness temperature and soil moisture. As in the thermal-infrared region, the microwave approach is applicable in the topmost 5 cm of soil in areas of bare soil or under cultivation. This technique also cannot be used in forested areas because the attenuation of microwave radiation increases with vegetation density.

Sensing of microwave emissions varies with the scan angle of the sensor and with surface roughness, limiting the use of the passive microwave technique to flat areas where the vegetation and soil conditions are known. The accurate determination of vegetation and soil types requires careful instrument calibration, which is generally difficult and very expensive. The errors associated with estimating the moisture content of bare soil using microwave radiometry can be as low as 1 percent (under the best conditions) but is more generally at least 5 percent. The most useful microwave frequency for soil-moisture determination is the L-band (1.4 GHz).

EVAPOTRANSPIRATION

The flux of moisture from the surface to the atmosphere by evaporation, transpiration, and evapotranspiration cannot be directly measured by remote sensing techniques. Nor can all the parameters necessary to compute these fluxes, including solar radiation, soil temperature, soil moisture, humidity near the ground, and wind velocity, be directly provided by remotely sensed data. To determine incoming solar radiation, for example, measurements are needed of the global radiation flux, that is, the radiation absorbed and reflected from the atmosphere and reflected from the ground (albedo). Techniques exist for determining the hourly, incoming solar radiation based on visible and infrared scanner data gathered by the geostationary GOES satellite. These procedures have errors in the 10–15 percent range. The radiation absorbed by the ground can also be determined from geostationary satellites by measuring the emitted terrestrial radiation flux, downward atmospheric flux, and surface albedo and then using these data to calculate the net input of heat into the soil.

Thermal-infrared and radar imaging systems have been used to determine the evaporation from bare soil surfaces. Methods employing these systems demand a good knowledge of soil characteristics because such characteristics are used in soil-moisture estimation. Soil water-transfer models are used because they yield estimates of the amount of water available for evaporation. The accuracy of these methods in large areas greatly depends on how well the different soil types can be mapped and how well the soil characteristics for the different soils and their moisture contents can be determined.

Thermal-infrared images from both airborne and spaceborne platforms have been used in conjunction with soil water and boundary layer models to estimate evapotranspiration. Since vegetation attenuates the thermal emission from the soil surface and also transpires water, methods have been developed in which the vegetation canopy temperature is used instead of the soil surface temperature. The primary source of error in this method is the accuracy of measuring the canopy temperatures. Interpretation of vegetation types is needed and, at present, the methods can only be used in cultivated areas, prairies, and savannas. Error estimates associated with such remote sensing methods range from 5 to 10 percent when in-place measurements have been available for use. At present there is no operational remote sensing method available for determining evaporation or evapotranspiration. Most recent research has focused on methods being developed for arid, semiarid, and cultivated areas.

SECTION 3: FUTURE RESEARCH IN REMOTE SENSING (ADVANCES, LIMITS, AND BARRIERS)

During our workshop discussions of the future applications of airborne remote sensing to geology, we identified a number of research topics that cover various aspects and are common to many applications. For the purposes of this report, the topics have been organized in three categories: (1) likely research advances—focusing on current trends and developments, (2) research needed to define the likelihood of success—identifying critical areas that need more attention, and (3) current barriers to future research—enumerating some concerns and needs of remote sensing professionals.

LIKELY RESEARCH ADVANCES

The field of remote sensing is changing rapidly as a result of dramatic developments in detector technology and computer processing. It is often difficult to predict what directions the field will take because the technology is progressing so quickly. Methods that appeared only as laboratory research a few years ago can now be discussed with confidence as probable airborne and satellite instruments. Spatial and spectral resolutions (and the accompanying data rates) continue to grow at an incredible pace compared to other developments in earth science. This first category describes where the research focus was at the time of the workshop. Applications based on these developments are likely since they involve a direct extrapolation of current work and do not require a major breakthrough in scientific or technological understanding.

INSTRUMENTATION

Airborne imaging spectrometers became a reality several years ago following the development of two-dimensional detector arrays that permit acquisition of high-resolution spectral and spatial data. The significance of this advance became apparent as mineral spectra from improved spectral-resolution laboratory instruments revealed structure in the near-infrared that had not been previously recognized. The spectra of a growing number of clay and carbonate minerals can now be identified in airborne data, and work is steadily progressing toward the application of this method to field studies. Parallel developments are beginning to occur in the thermal-infrared region, the region of the electromagnetic spectrum containing the primary molecular vibrations of silicate and carbonate minerals. Present technology is largely limited to general rock types, however, and improved instrument sensitivity, increased collection apertures, and reduced noise will be required, in conjunction with higher spectral resolution, to produce comparable advances to those in the reflective solar spectral region. Use of active sensors in the visible to infrared wavelengths has been shown to be feasible from aircraft. A controlled radiation source has advantages because a specific absorption feature can be monitored for mapping concentration changes and because in the thermal region the signal is independent of the surface temperature.

MINERAL-MIXTURE MODELS

Increased spectral resolution has made it feasible to map changes in mineral composition. Because the reflectance spectrum of a mineral mixture is a complicated function of the grain sizes and abundance of the minerals present, this area of research is critical for deriving mineral abundance from spectral measurements. Additional but secondary effects are related to packing and viewing geometry. In the last few years, physical models have been developed to predict mineral spectra. More recently, techniques have been devised to invert a spectrum in order to derive the abundance of each mineral in the mixture. Provided that sufficient spectral features are present in the observed radiance spectrum, even the grain-size distribution, in theory, can be derived. To date, laboratory measurements on carefully prepared samples appear to confirm these results. When well-calibrated imaging spectrometer data are collected, maps can be derived of selected minerals present and estimates of their abundance can be made. The development of a library of the optical constants of minerals as a function of wavelength is an important first step. Spectrum inversion requires substantial computer processing time with fast computers. Computational methods that employ spectral extraction and matching techniques are currently in use.

SURFACE ROUGHNESS

Although radar is extremely sensitive to surface roughness, interpretation of radar images is generally limited to relative roughness estimates within the same image, and comparison with images of other areas or from different radar systems is problematic. New quad-polarization, multifrequency radar offers the promise of limited data inversion to derive estimates of roughness. Although this work is in its infancy, the early results are encouraging for classifying geomorphic features.

LINEAMENTS AND MINERAL DEPOSIT CONTROLS

The relationship between different scales of lineaments and their degree of control of mineral deposits is a subject that continues to be investigated. Although shorter linear features can often be attributed to topographic features such as faults and strike valleys, the causes of longer lineaments are often enigmatic and difficult to relate to specific surface or subsurface expression. Several statistical methods have been employed to analyze lineament and linear-feature maps and recent focus on fractal aspects looks encouraging. The development of GIS has made it practical to compare topographic, geologic, geophysical, and geochemical data sets with remote sensing images quite precisely. This is a critical step in understanding lineaments, their causes, and their relationships to mineral deposits. The development of a range of remote sensing systems with spatial resolutions ranging from meters to kilometers now makes it possible to apply quantitative measuring tools such as fractal analysis, azimuthal trends, and spatial frequency distributions to the study of lineaments in a more thorough and less subjective manner.

Much future research on lineaments and their relation to ore deposits needs to be done to fully understand their relevance to metallogenesis. Modeling of lineaments and their related geologic structures with regard to local and regional tectonic environments is essential to understanding the relationships of lineaments to geologic "plumbing" systems and mineral deposition. The extent of remote-sensing-system ground resolution of surface expression must be investigated with respect to the type of structures that can be identified. There are already indications that Landsat MSS data (now largely replaced with TM) are too coarse for analysis of individual mine properties; likewise, high-detail aerial sensors may miss regional features because of the "forest versus the trees" effect. An area of study that may provide answers to some of these concerns is the "multilevel investigation" approach where specific deposits or mineral districts are analyzed using sensors on various airborne and spaceborne platforms (with different resolutions) in conjunction with multiple but complementary geophysical techniques and in-mine observations. Such an approach could provide a detailed three-dimensional assessment of structurally controlled deposits, which can be used to construct a model for similar deposits. These deposit models could be used to assess the potential of remotely sensed features such as lineaments as exploration tools for mineral deposits on a local and regional scale.

SIGNATURES OF HYDROCARBON MICROSEEPAGE

The mineralogic, geochemical, and geobotanical signatures of hydrocarbon seepage at the Earth's surface are topics of increasing research focus. Seepage-related signatures do not result in uniform or even closely similar mineralogic and botanical contrasts over different areas, even within the same basin. Factors that control the type and distribution of plants and secondary minerals that may be related to, or affected by, seepage include the composition and evolution of the seeping hydrocarbons; related bacterial activity; the composition, structure, and hydrology of the bedrock between the reservoir and the surface; and climate, as well as other factors that control soil development and types and distributions of flora (including vegetation stress).

At this stage, the targets for remote sensing of the effects of hydrocarbon seepage are not fully defined. Tenuous knowledge of such effects in bedrock at and near the surface nevertheless far exceeds the knowledge of even more subtle, subdued, and masked manifestations of seepage in soils. Field and laboratory research on the mineralogic and botanical signatures of seepage, especially in soils, will enhance the capability of remote sensing techniques for oil and gas exploration. More work on identifying minerals and on mineralogic associations related to seepage, tied to laboratory studies of spectral properties, may lead to development of new methods of remote sensing detection or novel applications of established techniques. The clay minerals in particular seem to offer high potential as targets for research in light of enhanced resolution methods. However, knowledge of the spectral ranges of clays as functions of crystal chemistry, and of the effects of hydrocarbons on clays in soils, is lagging far behind the capacity of remote detectors to measure spectral features.

RESEARCH NEEDED TO DEFINE LIKELIHOOD OF SUCCESS

This category is used to identify critical areas of research that require further work. They represent frontier areas in which the discussion groups felt remote sensing has the potential to make a significant contribution, but such contribution remains uncertain because key issues have not been resolved and critical experimental results are lacking. These are often the areas that are difficult to fund because results, although encouraging, are controversial and cannot be guaranteed. Many of these issues are not new. The topics identified in this section have been under various forms of discussion for over a decade and yet only radar penetration appears any closer to resolution. The need for well-designed, critical experiments remains.

LINEAMENTS

Despite the widespread use of lineaments in defining the geologic structure of the Earth, there is relatively little understanding of how they really relate to the tectonic environment in which their controlling structures formed. This is true for all scales of lineaments, from the most lengthy to the most local. Perhaps this lack of understanding is truly what is at the heart of criticisms of the method of lineament analysis. That which is little understood is many times most disdained.

To remedy this situation, several areas of research need to be pursued. One of the most basic areas is the determination of the depth versus size and scale of lineaments. We already know that very short lineaments may not extend to a significant depth. Is the converse true concerning very large lineaments? If so, why? Quantitative understanding of how structures that appear as lineaments relate to the regional or local tectonic environment is lacking. We often can point to an orogenic or other deformational event (such as the extension that is causing the Basin and Range faulting) and say that the fractures that are parallel and perpendicular to the resulting structures from that event are probably caused by the event as well. However, the formation of such fractures is poorly understood, especially when there is overprinting from multiple events. Quantitative determination of the stress fields that produced the fracture systems (and, therefore, lineaments and lineament trends) would be an invaluable tool for unravelling structural overprinting and dissecting tectonic history.

In a local sense, the effects and timing of valley rebound become important. Valley rebound is a stress-relief event that occurs when erosion removes material over time from a valley, and remanent tectonic stresses in the terrane cause the valley bottom to move upward because of the stress relief in the valley and the relative "squeeze" from adjacent and underlying material. Because many valleys are included as lineaments in an analysis, the fractures seen in these valleys may be caused by the rebound rather than deep-seated geologic structures. Based on geomorphologic principles, one would think that preexisting fracture patterns (if any) would be likely to control erosion and, therefore, any valley rebound. This relationship needs to be understood more completely. In addition, there may be some connection between lineament trends, their controlling structures, the depth to which these structures extend, and the trends of structures along which valley rebound occurs. These interrelationships may have bearing on the stability of underground mines in the vicinity of such rebound and controlling structures.

VEGETATION STRESS

Because vegetation cover is extensive in nonarid areas, knowledge of plant ecology is essential to understanding the remote sensing expression of plant communities. In the visible and near-infrared spectral regions, the spectral curve for all green deciduous vegetation has the same general shape. Spectral variations occur with changes in water content, with reflectance differences between leaves and needles, and with stress caused by drought, insect damage, or the presence of excessive metallic elements in the soil. In order to understand the data, known plant and substrate relationships should be quantified and further relationships should be established in field studies. Mechanisms for the processes by which stresses on plants and changes in floral composition affect the reflectance of plant communities also need to be understood more clearly and quantified where possible. More research is needed to determine whether specific causes of spectral effects can be distinguished.

In arid regions, vegetation spectra vary with epidermal appendages (hair, thorns, and waxy cuticle), and because canopies are rarely closed, soil, rock, and vegetation contribute to the overall measured signal from each resolution element (pixel). In both humid and arid regions, models of scattering from complex canopies need to be developed and quantified. In the thermal-infrared, spectral variations among plant species and stress-induced temperature changes in vegetation have been reported and need to be evaluated. Airborne data are critical for these studies because of the need for moderate-to-high spatial resolution.

RADAR PENETRATION

Satellite data have been used to demonstrate that L-band (30 cm) radar can penetrate as much as a meter of hyperarid terrain. The attenuation rises rapidly with increased soil moisture, however, and extension of this approach to arid and semiarid terrain of the Western United States will require additional experimenting with multiple-wavelength radar and improved modeling to reduce effects of surface and subsurface scattering. Because the radar signal is very sensitive to soil moisture, it has the potential of providing indirect evidence of structural control in alluvium-covered areas. This could be coupled with thermal data, which have a somewhat shallower capability but have been acquired more extensively and with higher spatial resolution from aircraft.

CURRENT BARRIERS TO FUTURE RESEARCH

The workshop provided a vehicle for a group of remote sensing professionals to discuss their research and its extensions in application areas beyond the confines of their current or past work. The discussions illuminated some areas that are primarily of interest to researchers rather than program managers. The issues relate to barriers that affect future research rather than immediate concerns and can serve as a useful signpost of how well (or poorly) a group such as this can project and predict. Rapid developments in computer systems suggest that it is difficult to predict developments in a field that is so tied to technical innovation and swift change. The comments about the work force probably parallel similar views in the rest of earth science. The continuing ups and downs in the job market, coupled with the long lead time to develop a researcher, virtually insures that this problem will continue to be with us. As computer literacy and availability of remote sensing data continue to grow in the earth sciences, a new cadre of scientists will evolve that will incorporate into their work many of the functions that remote sensing researchers now perform. Remote sensing research would then be conducted as a more focused, less applications-oriented activity.

DATA VOLUME

The advent of the airborne imaging spectrometer has produced data sets that are capable of overwhelming present research computer facilities. A single 10- by 12-km scene from the 224-channel NASA AVIRIS contains as much digital data as a 185- by 185-km scene from the 7-channel Landsat TM. To put the problem in a broader perspective, it is anticipated that by the turn of this century the NASA data archive will have grown to the point that if the data were stored on high-density (6,250 bpi) magnetic tapes, the stack would be 60 km high! Fortunately, optical storage technology results in a substantial data-volume compression. Data processing throughput (storage/retrieval/processing) remains a significant constraint for large-scope national programs.

AVAILABLE DIGITAL DATA

Some remote sensing data are available only in analog form, and the increasing use of GIS requires the conversion of these data into digital form. Recent studies made in mineral assessments of a 1°×2° quadrangle show that it may take up to half a year to digitize and coregister the data that takes only a month to analyze!

In order to create stereoscopic images for extraction of structural and lithologic information, high-precision digital elevation models are required. At present, this type of data is available for only a fraction of the United States and an even smaller percentage of the whole world. Present satellite systems are not able to produce such data at required map-accuracy standards.

DATA FORMATS

Currently, a variety of digital data exist in Federal, State, and local government agencies and in the private sector in different formats and topologic structures. The U.S. Department of the Interior Digital Cartographic Coordination Committee (IDCCC) and the Federal Interagency Coordination Committee on Digital Cartography (FICCDC) have organized study teams to define an acceptable national standard exchange format for digital data. Although this format will promote increased use of existing data, refinements will require considerable in-house expertise to use these data. The USGS has developed a standardized grid-exchange format for its data sets. Developers and users of airborne remote sensing systems will need to be knowledgeable about prevailing formats and data structures.

Growth in the application of digital techniques, and access to personal computers by the geologic community has increased data availability to a diverse group of users. Current barriers to exchange of digital data relate to rapid changes in technology more often than to institutional considerations. Data capture is the most time-consuming aspect of performing digital analyses, and establishing common formats will result in more efficient exchange and wider utilization of data.

RESEARCH WORK FORCE

As in other areas of scientific technology, future developments in remote sensing will depend on a vigorous and well-motivated research community. It is difficult for most academic institutions to prepare students for remote sensing research because of the breadth and depth of disciplines that now use the technology. Often, university research is constrained by the availability of funds, and these are often targeted for specialized but short-lived instrument hardware and data collection. As the technology becomes more complex, a larger infrastructure is required to support research. This produces a "chain" of expertise that tends to distance the scientist from a comprehensive understanding of the science and the analysis methodology. The newest instruments and their applications require students with a broad grasp of the principles of physics, geology, and chemistry and expertise ranging from field mapping to computer analysis.

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Published in the Central Region, Denver, Colorado
Manuscript approved for publication May 21, 1993
Graphics prepared by Patricia L. Wilber
Photocomposition by Shelly Fields

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☆U.S. GOVERNMENT PRINTING OFFICE: 1994- 573-038/86023

Watson and Knepper, eds.—AIRBORNE REMOTE SENSING FOR GEOLOGY AND THE ENVIRONMENT, PRESENT AND FUTURE—U.S. Geological Survey Bulletin 1926