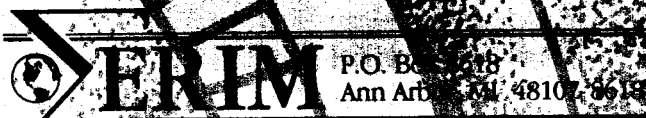


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THEMATIC CONFERENCES ON REMOTE SENSING
FOR EXPLORATION GEOLOGY

SUMMARIES

7th Thematic Conference
Calgary, Alberta, Canada
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PREFACE

The Thematic Conference series was initiated to address the need for concentrated discussion of particular remote sensing applications. The First Thematic Conference, "Remote Sensing of Arid- and Semi-Arid Lands," was held in Cairo, Egypt, in January of 1982; the Second, Third, Fourth, Fifth, and Sixth Thematic Conferences, "Remote Sensing for Exploration Geology," followed in Fort Worth in 1982, Colorado Springs in 1984, San Francisco in 1985, Reno in 1986, and Houston in 1988, respectively. The current conference, which also addresses "Remote Sensing for Exploration Geology," continues the series of meetings concerned with the application of remote sensing in exploration programs. The program is primarily concerned with the application of remote sensing to mineral and hydrocarbon exploration, with special emphasis on data integration, methodologies, and practical solutions for geologists.

This volume contains summaries and/or abstracts of papers scheduled for presentation, including those selected from contributions in response to the Call for Papers, as well as those invited by the Program Committee.

Some fifty invited papers are scheduled for eleven plenary sessions, formulated to address such important topics as basement tectonics and their surface expressions, spectral geology, applications for hydrocarbon exploration, and radar applications and future systems. Other invited presentations will discuss geobotanical remote sensing, mineral exploration, engineering and environmental applications, advanced image processing, and integration and mapping.

Further, in the interest of stimulating and encouraging more significant and effective communication, all contributed papers selected for presentation at the current meeting, as well as others specifically invited by the organizing committee, have been included in six comprehensive poster sessions consisting of some 200 papers.

This volume of summaries and abstracts is intended to assist you in identifying the sessions and presentations of greatest personal interest. You are encouraged to review this volume before attending the various sessions. All summaries received in time for publication are presented below.

For the Program Committee,



Robert H. Rogers



Nancy J. Wallman

THE POSTER SESSION FORMAT

As noted in the Call for Papers for this conference, all papers selected for presentation have been included in six multi-disciplinary poster sessions. In addition, many of the invited papers scheduled for presentation in the conventional sessions will also be presented, or supported by companion papers, in the various poster sessions.

Experience has shown that the poster session format is in many ways optimum for technical presentation in the field of remote sensing, where imagery, photographs, charts, graphs, maps, and overlays are often more important and informative than textual material. Their utilization in the Thematic Conferences is an attempt to foster more efficient and effective presentation, and to encourage in-depth discussion and interaction to a greater degree than is possible with more conventional modes of presentation.

These summaries have been provided to give you the opportunity to review the papers in each session ahead of time, so that you can select the ones of greatest personal interest and obtain some background for subsequent discussions with the authors. The organizers welcome your suggestions for refining and improving the poster session format; contact Robert Rogers or any member of the Program Committee with your ideas about how the poster sessions could be made even more useful to attendees.

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REMOTE SENSING AND FIELD MAPPING OF TERTIARY FAULTS,
SOUTHEASTERN ELLESMERE ISLAND,
ARCTIC ARCHIPELAGO: BASEMENT SLIP AND COVER RESPONSE

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SUMMARY

On southeastern Ellesmere Island, Precambrian crystalline basement is overlain by about 6000 m of Cambrian to Devonian carbonate and evaporite strata of the Arctic Platform. Evaporite occurs in two distinct Ordovician formations. Interpretation of low level aerial photographs of this region (previously mapped only during reconnaissance by dog sled 30 years ago), showed very pronounced SW-trending lineaments, small anticlines with N-S axes, grabens with NW strike, E-trending normal faults, and enigmatic detachment faults.

Field mapping showed that these features were part of a large strike-slip and extensional regime and regional interpretation has suggested this regime is related to rifting in Baffin Bay. The SW lineaments are dextral strike-slip faults lying SW of a NW-trending rift system. N-S folds and minor reverse faults are consistent with dextral transpression. Spatially associated detachments may be related to local dextral transtension. E-trending normal faults are a branch from the main rift, localized by sub-parallel structural fabric in the basement.

The response of sedimentary cover to basement movements varied. Formations below the lower evaporite remained attached to the basement, while those above were folded and faulted. Away from the zone of dextral strike-slip, folds and detachment faults are absent and only NW-trending grabens parallel to the primary rift are present. The complex response of cover results from differing interactions, at various stratigraphic levels, among competent and incompetent strata, old structural fabric of the basement (whose trend changes over the area), and the superimposition of Tertiary rifting and strike-slip faulting.

Although the mineral and hydrocarbon potential of the region is considered minimal at present, there may be some parallels between fault patterns in platformal strata of this area and those from southwestern Ontario. There, some hydrocarbon traps are the result of fracture rejuvenation and fault block rotation.

MAPPING OF BASEMENT AND OTHER TECTONIC FEATURES
USING SEASAT AND THEMATIC MAPPER IN
HYDROCARBON PRODUCING AREAS OF ALBERTA AND SASKATCHEWAN

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SUMMARY

This study examines the uses of satellite radar (SEASAT) and Landsat Thematic Mapper (TM) images for mapping sub-surface structures that may have influenced the distribution of hydrocarbons within the sedimentary rocks of Western Canada.

Seasat SAR and Landsat TM images of the entire Western Plains region of Alberta and Saskatchewan have been interpreted to map faults, circular, (dome) features, present and paleo drainage channels, and other mappable geological anomalies. Five sub-areas (Calgary, Peace River, Edmonton, Steen River, and Swift Current), each representing a different geological environment, were selected for more detailed study. For each sub-area, Seasat and TM data have been digitally coregistered with other data sets, including geology, magnetics, gravity, and oil well data, and are processed using image analysis and GIS techniques.

The Western Plains are transected by two sets of faults trending in NE-SW and NW-SE directions. Other studies from Alberta and Saskatchewan have confirmed the presence of these major fault trends.

The NE-SW fault set extend westward from the exposed Canadian shield. Many of these faults have magnetic anomalies associated with them, which would indicate that they are formed by continuation of lineaments within the basement. High resolution SAR images show that those magnetic linears are represented at surface by a broad zone of fault traces. Many of these faults coincide with the margins of sedimentary basins that were formed in Paleozoic times.

The NW-SE trending faults are parallel to the Rocky Mountain Front, and do not have magnetic anomalies associated with them. This suggests that they may originate in tectonic events that postdate the NE-SW fault set.

An analysis of the producing oil wells suggests that although most of the active oilfields are associated with paleo-shorelines, reefs, drainage channels, and depocentres, many of these hydrocarbon traps also coincide with mapped lineaments. In the western margin of the plains region, many of the active oil fields are elongated in a NW-SE direction. Along the eastern edge of the Plains region, many of the active oilfields are elongated and aligned in a NE-SW direction.

SATELLITE IMAGERY LINEAMENTS AND THEIR RELATION TO FACIES TRENDS,
STRUCTURE, SALT DIAPIRISM, AND OILFIELD PRODUCTION PATTERNS
IN THE ZAGROS FOLD BELT OF SOUTHWEST IRAN

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SUMMARY

Extensive field observations over a large tract of continuous rock outcrops in the Zagros Mountain Range of southwest Iran have yielded a wealth of stratigraphic and structural detail. In that region, structural anomalies are frequently associated with similar facies distribution patterns. In the eastern portion of the region, emergent salt plugs of infra-Cambrian age exhibit the same alignment patterns. Such trends bear no apparent genetic relationship to the Tertiary folding responsible for the present fold belt grain of the Zagros range but rather indicate their affinity with linear basement features which are readily observable on Landsat imagery and air photographs.

Superimposed on the eastern region's mode of facies trends and structure are localised variations which are directly attributed to pulses of salt diapiric activity. Thus, stratigraphic data acquired from deep sections associated with salt domes can lead to erroneous overviews of regional facies distributions while anomalous dome shaped structural features associated with elongate folds, so common to the fold belt, can only be attributed to near surface diapiric structures.

The recognition of features related to basement tectonics and the realization of their implication in the control and modification of geological processes is an important adjunct to the search for hydrocarbon accumulations in the region. Indeed, it can be shown that renewed movements on basement trends directly affect oil production patterns as a consequence of the enhancement of fracture porosity and permeability in Tertiary carbonate reservoir structures. These constitute some of the world's largest producing oil fields.

THE CONTRIBUTION OF AN INTEGRATED ANALYSIS OF SATELLITE IMAGERY,
GRAVITY, AND MAGNETIC DATA TO THE RECOGNITION OF
STRUCTURAL/STRATIGRAPHIC TRAPS IN THE ALBERTA BASIN, CANADA

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SUMMARY

Fluvial channels and shoreline sand bodies of Cretaceous age constitute significant reservoirs in the Alberta Basin, Canada. These sand bodies form stratigraphic traps that appear to be localized in relatively short linear or arcuate segments of incised valleys and other paleotopographic depressions. Exploring for these types of hydrocarbon traps is difficult because they are subtle and difficult to detect on seismic data. Furthermore, in many instances the spatial distribution of these traps appears to be random and unpredictable.

An integrated analysis of Landsat imagery, gravity, and aeromagnetic data was conducted to test the hypothesis that the location of these sand bodies was controlled by syndepositional topographic features related to deep-seated structures. The results of this study show that the location of several producing fields in the Alberta basin has been influenced by the presence of subtle topographic features that developed in response to basement structures as well as buried Devonian reefs. This effect on sedimentation was particularly evident during the deposition of Mannville Group (lower Cretaceous) sand units. Several of the producing sand bodies appear to be localized in incised valleys and other topographic depressions that developed around deeper domal structures as well as around buried Devonian reefs. These structures can be detected through an integrated assessment of Landsat imagery, gravity, and magnetic data. Furthermore, the influence of these structures on sedimentation can be predicted using stratigraphic/structural models derived from experimental and modern analogues.

CONCEPTS AND ADVANCEMENTS IN SPECTRAL REMOTE SENSING FOR GEOLOGY

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SUMMARY

Historically, the advent of earnest research into the uses of spectral remote sensing in geology came in the early sixties with the declassification of multispectral scanner technology and the development of semiconductor detectors. Research also got a boost from the lunar and planetary program which had to derive its information about planetary surfaces almost exclusively from remote sensing. The launch of ERTS-1 in 1972 gave most geologists their first experience with multispectral data from regions beyond the visible spectral region and, together with the new techniques of digital image processing, they made rapid advances in interpretation of spectral data, particularly in resource exploration applications. Color ratio compositing, first developed then, is still in use today.

The seventies saw much activity in the development of spectral data bases from field as well as laboratory instruments, in both reflection and emission. Aircraft multispectral scanners with coverage beyond 1 μm , along with field spectral measurements, provided the rationale for the 7th band on Thematic Mapper which has proved invaluable for mapping OH and CO₃-bearing minerals. The beginning of the eighties saw the development and deployment of the Thermal IR Multispectral Scanner and the Shuttle Multispectral IR Radiometer. The latter produced the first direct identification of kaolinite and limestone from orbit and paved the way for the development of imaging spectrometry.

Imaging spectrometry provides the opportunity for direct identification of earth surface materials and as such has stimulated the development of a variety of sensors and has severely challenged the community to develop interpretation tools. In the sensor area, the Airborne Imaging Spectrometer and the Airborne Visible and InfraRed Imaging Spectrometer have been developed by NASA, while Geophysical Environmental Research has developed an imaging spectrometer for commercial use. NASA is developing the High Resolution Imaging Spectrometer for flight aboard the Polar Orbiting Platform in 1997. The Japanese Intermediate Thermal Infrared Radiometer is also slated for the Platform.

Analysis tools being developed today revolve around identifying individual minerals in a pixel by binary vector and band center/shape using selection rules, and calculating abundances of individual components of a pixel from image or library spectra using unmixing techniques. The new hardware and software developments will truly revolutionize the applications of spectral remote sensing in geology.

LITHOLOGIC MAPPING USING AVIRIS DATA NEAR MOUNTAIN PASS, CALIFORNIA

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SUMMARY

Airborne visible/infrared imaging spectrometer (AVIRIS) data of the Mountain Pass area in southeastern California were examined to assess the use of this type of data for regional lithologic mapping. Lithologic units in the area include Precambrian gneisses and schists, Paleozoic carbonates, sandstones, shales, and Tertiary volcanic rocks. The numerous ore deposits include small copper deposits as well as a major rare-earth deposit related to the Mountain Pass carbonatite complex.

Three flightlines of AVIRIS data were acquired by the NASA ER-2 aircraft on July 28, 1987. At the altitude flown (20 km), the instrument has an IFOV of 20 m and has a swath width of 11 km. The data provide 210 spectral channels spaced 9.8 nm apart throughout the visible and near-infrared (0.4 to 2.45 μm) a region where many minerals exhibit diagnostic absorption bands.

No spectrally featureless calibration targets exist in the study area suitable for performing a "flat field" correction to normalize the AVIRIS data; the alluvium has extensive rock pavement surfaces and abundant Mohave desert-type vegetation. To avoid normalization, we generated relative absorption band-depth (RBD) images directly from the radiometrically corrected data. To construct an RBD image, data channels are selected that correspond to the minimum and shoulders of a mineral absorption feature. The digital number (DN) values of shoulders are summed as are the DN values of channels positioned at the absorption minimum. The summed shoulder values are then divided by the absorption minimum values. As many as nine AVIRIS spectral bands were combined in each RBD image. To decide which images to generate, diagnostic mineral absorption features were identified from laboratory spectral reflectance measurements of rocks collected from the study area. Prior to the RBD image generation, a 5 x 5 pixel spatial filter was applied to the data to increase the effective signal-to-noise. The RBD band combinations that were examined included band centers at 2.20 μm (to detect clays, micas, and gypsum), 2.25 μm (to detect chlorite and jarosite), and 2.31-2.33 μm (to detect carbonate minerals).

Despite the signal-to-noise limitations in this early AVIRIS dataset, the ability to distinguish lithologic and structural features in the study area was impressive. The RBD images permitted the separation of all the major lithologic units, and in several areas revealed units that were not shown accurately on the available geologic map. Of particular interest was the ability to distinguish differences in the composition of alluvial material derived from different bedrock units. This ability was useful for discerning and tracing faults in areas of limited bedrock exposure. The rather extensive vegetation cover (20-50 percent) was not enough to mask the basic compositional signature of the rock/soil mineralogy.

MINERALOGICAL MAPPING WITH IMAGING SPECTROSCOPY
FOR PRECIOUS METALS EXPLORATION

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SUMMARY

Exploration geologists are well aware of the common minerals associated with the alteration zones of mineralized deposits. They are equally well aware of how difficult it can be to identify these minerals in the field. Reflectance spectroscopy provides a means for quickly and accurately mapping the surface mineralogy both in the field and with remote sensing instruments. The mineralogy of hydrothermally altered rock at the surface is related to the original minerals present in the rock and chemical changes produced by alteration and weathering. Laboratory studies of the visible and near-infrared spectral properties of rocks and minerals indicate that many individual mineral species can be identified based on their spectral characteristics. Physical and chemical changes produced by alteration can also be detected because many common alteration minerals have characteristic spectral features between 2.0 and 2.5 μm . The position and shape of these absorption bands allows identification of minerals such as kaolinite, alunite, illite, montmorillonite, calcite, dolomite, and many others, while the depth of the bands allows semi-quantitative estimates of surface abundances.

A new multispectral remote sensing instrument called an "imaging spectrometer" pioneered by NASA collects near laboratory quality reflectance spectra and makes direct mineral identification from aircraft data possible. Imaging spectrometers acquire images in many narrow, contiguous spectral bands simultaneously. Analysis in the spectral domain allows extraction of a detailed spectrum for each picture element of the image, while image display of spectral information results in detailed mineralogical maps. Based in part on the success of the NASA imaging spectrometers and on demand from the mining and petroleum industries, Geophysical and Environmental Research Corporation (GER) developed a 63-channel high spectral resolution scanner for commercial use. The GER imaging spectrometer (GERIS) qualifies as an imaging spectrometer in the true sense of the definition as it acquires 63 inherently coregistered data channels simultaneously, produces continuous spectra, and retains the image format. It differs from other imaging spectrometers, however, in that the spectral bands vary in width across the spectrum.

This research uses the GERIS covering the spectral region 0.4 to 2.5 μm to look at several precious metal deposits in Nevada, USA. The data were calibrated to reflectance using field spectral measurements, spectra were extracted, and individual minerals identified by their spectral characteristics. Images were classified in the spectral domain to produce color-coded image maps of mineral distribution that clearly show the zoned nature of several hydrothermal systems. Comparison of the thematic mineral maps with existing geologic and alteration maps demonstrates the utility of imaging spectrometers for producing detailed maps for mineral

exploration. Identification of individual minerals and spatial display of the dominant mineralogy using the imaging spectrometer data adds information that can be used in determining the morphology and genetic origin of the deposits. This research demonstrates that imaging spectrometers can be a viable part of a precious metals exploration effort. Integrated use of satellite remote sensing and selected imaging spectrometer aircraft coverage can be a powerful tool in guiding the initial stages of property assessment and development, to quickly produce detailed maps for previously unmapped areas, and to supplement existing geologic mapping.

USE OF MULTISPECTRAL THERMAL INFRARED REMOTE SENSING IN EXPLORATION GEOLOGY

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SUMMARY

Multispectral thermal infrared (TIR) remotely sensed data has been demonstrated to contribute to exploration through improved geologic mapping. Some important mineral groups, such as the silicates, are better differentiated using TIR data than visible-near infrared (VIR) or shortwave infrared (SWIR) data. The best geologic remote sensing for exploration will be achieved by using a combination of data from all three wavelength regions.

The NASA airborne Thermal Infrared Multispectral Scanner (TIMS) has now been flown over areas of geologic interest in the United States, Australia, and Europe, and the exploration potential has been clearly demonstrated. Some selected examples include mapping of the alteration zones associated with mineralization Goldfield, Cuprite and other areas of Nevada, and sedimentary basin stratigraphic mapping in Wind River Basin, Wyoming.

Use of multispectral TIR for exploration has been limited in the past by lack of sensors. There have been only two or three aircraft sensors, which are costly and have very limited availability. Now, for the first time, there is a scheduled orbital mission which will include multispectral TIR bands at a spectral resolution sufficient to allow geologic applications. This is the Japanese instrument ITIR, which has been designed specifically for exploration. Current plans call for three bands in the VNIR with 15 m resolution and stereo capability, six bands in the SWIR with 30 m resolution, and five bands in the TIR with 90 m resolution. This instrument is scheduled to fly on NASA's first EOS polar platform circa 1996. Other orbital TIR missions being considered include possible addition of TIR bands on Landsat 7, and a dedicated Earth Probe satellite.

THE SPECTRAL REFLECTANCE OF MINERAL MIXTURES
IN THE MID-INFRARED (7-25 μm)

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SUMMARY

The mid-infrared region of the spectrum has been used for remote sensing less than the visible and near infrared. However, there is extensive mineral and rock compositional information in the mid-infrared because it contains the fundamental molecular vibration bands of all the major rock-forming minerals. It has been suggested that, contrary to experience in the visible and near-infrared, a linear mixing model can be used in the mid-infrared. This work thoroughly documents for the first time that mineral spectra do indeed combine linearly to form the spectra of mineral mixtures in the 7 to 25 μm portion of the mid-infrared spectrum.

Mineral samples of quartz, microcline, plagioclase, pyroxene, and olivine were ground to a 75-250 μm particle size range. Spectral reflectances of pure minerals and various mineral mixtures were measured on a Nicolet 5 DXB interferometer spectrometer. Reflectance spectra of mineral mixtures were then compared with spectra calculated by linearly combining pure mineral spectra in the appropriate proportions, with the result that the calculated spectra closely reproduce the measured spectra of mineral mixtures.

These results suggest that the spectral response of a rock can be predicted if the constituent minerals and their proportions are known. More important, the spectrum of rock can, in principle, be deconvolved to derive both mineral types and abundances. This is important for remote sensing applications and laboratory rock identification. In addition, a better understanding of the reflectance properties of minerals and rock makes possible a better choice of band position and width for multispectral remote sensing measurements.

PHOTOGEOLOGY A REMOTE SENSING EXPLORATION TOOL
IN THE CALGARY - BANFF AREA OF ALBERTA, CANADA

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SUMMARY

The interpretation of vertical aerial photographs was used extensively in oil, gas, and mineral exploration in Canada starting around the 1950's and Calgary was a main photogeological mapping business center. For about twenty years the author was actively involved in part of this photogeological exploration action. Initially this participation was in the consulting business and later as an oil company employee specializing in photogeological techniques.

Brief case histories presented from the immediate Calgary - Banff region illustrate the application of photogeological techniques and their important contribution to exploration. Examples of mapping in the disturbed belt of the Rocky Mountains and the Rocky Mountain Foothills as well as the relatively undisturbed Plains area from 1954 - 1974 illustrate the role photogeology played in mapping exploration targets like the Devonian reefs and overthrust Mississippian plates such as that on which the Jumping Pound Field is located. Included are structural and stratigraphic mapping, the integration of photogeological mapping to the subsurface, fracture and lineament analysis, surface seismic access and surficial deposit mapping.

The case histories are used to illustrate the strengths and limitations of direct photogeological techniques as part of a complete exploration program. Photogeology is an inexpensive exploration tool that, as yet, is superior to imagery analysis. The stereoscopic analysis of aerial photographs is a remote sensing method that should still play an important, initial part of any onshore exploration program.

PETROLEUM EXPLORATION AND POTASH MINE DEVELOPMENT
STUDIES USING INTEGRATED PHOTOLINEAMENT,
GEOLOGIC, GEOCHEMICAL, AND GEOPHYSICAL DATA ANALYSIS

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SUMMARY

We present photolineament data that have been integrated with geologic, geophysical, and geochemical data for petroleum exploration and potash mine development in southern Saskatchewan. Seven studies have been made since 1986. Details considered proprietary are not included. Nevertheless, imagery analyzed, models and mechanisms envisaged, approaches followed, and many of the results are presented and discussed.

Measured orientations of fractures in potash mines located 1000 m underground and anomalously high hydrocarbon gas seepages along prominent photolineament zones suggest that surface and deep fracture and lineament systems can be closely related. Features interpreted from structure contour and isopach maps of sedimentary strata ranging in age from Cambrian to Holocene indicate that deep faults and fracture zones have influenced sedimentation and post-depositional processes through time. The disposition of suborthogonal sand-filled Jurassic channels near Shaunavon is one example.

Correlation of regional subsurface water-flow patterns, solution features in the Prairie Evaporite Formation, subsurface fracture zones, and fracture-lineament zones and their intersections point to fracture-controlled dissolution in Prairie Evaporite strata. The effects of evaporite dissolution processes can be important in planning potash mining operations as well as in oil and gas exploration and exploitation. In addition, regional magnetic and gravity trends frequently correlate with fracture zones and other structures underlying strong regional photolineaments and photolineament sets.

The Interior Plains of western Canada are underlain by gently dipping, relatively little disturbed Phanerozoic strata. In many locations mapped using remotely sensed techniques, recurring zones of weakness in the sedimentary rocks appear to originate in the underlying Precambrian basement, perhaps reflecting deep crustal zones of weakness.

The interpretation of integrated near-surface soil gas and photolineament data is effective in identifying fracture zones that act as vents for hydrocarbon gas microseepages originating in oil and gas reservoirs. Light hydrocarbon magnitudes and diagnostic soil gas ratios appear to be closely related to surface lineaments and correlated subsurface geologic and geophysical data. Such correlations may be used to identify areas that are prospective; to make inferences about whether reservoir hydrocarbons are likely to be gas, gas condensate, or oil in composition; and to upgrade exploratory oil well drilling locations.

Studies in progress are being directed toward soil gas sampling to identify fracture zones that may serve as pathways for water flow into potash mines. Risk mapping and analysis based on photolineament data correlated with subsurface geological and geophysical data are being evaluated for long-range potash mine planning. Techniques presented in this paper will be used to recommend locations for detailed geophysical surveys before mining begins.

**OBSERVATION OF SPECTRAL VARIATION INDICATIVE OF KEROGEN-TYPE
AND CATAGENETIC BIOMARKERS IN REFLECTANCE SPECTRA OF SOURCE ROCK:
THE APPLICATION OF REMOTE SENSING TECHNOLOGY TO PETROLEUM GEOCHEMISTRY**

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SUMMARY

The application of spectral remote sensing technology to organic geochemistry and, in particular, to petroleum geochemistry, has permitted observation of organic geochemical variation in samples essentially unaltered from their natural state. Visible region absorptions characteristic of porphyrin biomarkers and near-infrared overtones indicative of kerogen type have been identified in the visible and near-infrared reflectance spectra of oil shales and oil source rock. Laboratory calibration of reflectance spectroscopy for this application should permit certain organic geochemical studies to be performed in the field. In addition, it may be possible to detect surface outcrops of organic-rich deposits using remotely sensed spectral data.

The porphyrin class of biomarkers are the degradation products of chlorophyll-a. They are nearly ubiquitous in oils, oil shales and oil source rocks. High resolution, high precision reflectance spectra (~0.3-2.5 μm) of porphyrin characterized shale samples have been recorded and the porphyrin spectral contribution isolated. The samples represent endmember and intermediary cases of the porphyrin geochemical variation found in the late diagenetic and catagenetic thermal sequence. A "semi-empirical" approach to spectral deconvolution that mathematically models absorptions as gaussians has been applied to the porphyrin signature of each sample. The derived spectral features have been correlated with the samples porphyrin population.

A similar approach to deconvolution has been taken to identify and isolate near-infrared absorptions associated with the aromatic and aliphatic fractions of the sample. These near-infrared absorptions are overtones and combination modes of the vibrational absorptions observed in the mid-infrared portion of the spectrum. While overtones are inherently less intense than the fundamental absorptions, the effects of particle size in the near-infrared region of the spectrum are more systematic and, therefore, more easily understood.

The results of this study show that systematic, quantifiable spectral variation occurs parallel to organic geochemical variation in samples of oil shale and oil source rock. This spectral variation can be related to porphyrin geochemical parameters that are indicative of the conditions of deposition and thermal maturity. Near-infrared spectral variation is sensitive to changes in kerogen type. The observed organic absorptions are relatively intense such that porphyrin compounds have been observed at less than 10 ppm quantities.

This technique serves as a useful compliment to existing organic geochemical techniques by providing continuity between samples as well as providing an added verification to current methods. Moreover, the non-necessity of sample preparation may provide a basis for geochemical field studies and remote sensing surveys.

THE CONTRIBUTION OF SATELLITE INVESTIGATIONS TO EXPLORATION
IN WEST GERMANY AND SWITZERLAND

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SUMMARY

In this paper, we summarize the results of a Landsat study conducted jointly by the remote sensing group of Exxon Production Research Company and the exploration department of BEB, the largest oil and gas operator in West Germany. The study focused on two areas where conventional exploration has not been successful so far: the Swiss Molasse Basin and the southern part of the Lower Saxony Basin. In both areas, there is a known hydrocarbon in the system and available effective structural traps, but in both cases the reservoir is too tight for commercial production. The Landsat study aimed towards identification of structural traps that were enhanced by additional fault and fracture systems that have not been recognized by conventional mapping of seismic data.

Several, major basement reactivated fault systems were recognized in this study and the location of structural traps that are cross-cut by these structures have been identified and tested. In one case, a major fracture-related gas discovery was made.

We present the results of this study in three parts. First, we illustrate a step-by-step approach to the interpretation and integration of satellite imagery data. This approach is focused on the recognition of large-scale basement-related structures that produce expressions on Landsat imagery and gravity and magnetic data but are often difficult to detect on seismic because their expression is hidden by the more dominant expression of younger structures. Second, we demonstrate how this approach can lead to the development of exploration concepts that can be used to identify and rank structural leads in the region. And finally, we show how the concept was used to make a major discovery of the gas fields in the Lower Saxony Basin.

In the closing remarks, we compared the results of our approach to satellite imagery interpretation with the results of the more traditional Landsat lineament studies previously carried out in West Germany. We argue that our approach is more suitable to the exploration needs and practices of a major oil company.

HYDROCARBON EXPLORATION THROUGH REMOTE SENSING AND FIELDWORK
IN THE ONSHORE EASTERN PAPUAN FOLDBELT,
GULF PROVINCE, PAPUA NEW GUINEA

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SUMMARY

Over the Aure Tectonic Belt, in the Gulf Province of Papua New Guinea, several types of remote sensing have been acquired in the past and new data are collected regularly. For our onshore hydrocarbon exploration, we have used aerial photographs, Landsat Multi Spectral Scanner (MSS), and Synthetic Aperture Radar (SAR). SPOT imagery and Landsat Thematic Mapper (TM) were not available for our 1987/1988 investigation due to cloud cover on SPOT data and collection/transmission problems with TM in this part of the world. Onshore seismic is prohibitively expensive due to intense jungle coverage and difficulty in traversing the terrain, while the quality used to be very poor. Offshore seismic is available but very difficult to interpret.

The aerial photographs, at 1:100,000 and 1:40,000 scale, are of poor quality due to partial cloud cover, high sun angle, and general flat appearance. However, the resolution is very good. To get a true regional picture for our 6000 km² study area from aerial photographs is virtually impossible.

The Landsat MSS, at 1:250,000 and 1:100,000 scale, is of excellent quality as it was enhanced for geological purposes by EarthSat. The high sun angle, however, diminishes shadows to such an extent that subtle structures become invisible and the resolution, at 80 x 80 m, leaves much to be desired. The continuous rain forest cover obscures all exposures, but general structural trends are clearly visible.

The Synthetic Aperture Radar, at 1:250,000, 1:100,000, and 1:40,000, which was acquired in May/June of 1987, provided the first comprehensive view of the area. Because of the low,

artificial "sun angle", it revealed many structural elements that had not previously been recognized. Resolution after resampling was about 12 x 12 m which is sufficient in a forested area like this. High resolution radar (6 x 6 m) acquired over other parts of the South Papuan Fold Belt did not contain significantly better or more useful information.

Analysis of the available remote sensing sources revealed a more complex structural picture than displayed before on any geological map. There is a distinct difference in structural style between the northern onshore part of the study area and the southern onshore part. The northern part shows open folding with widely separated anticlines embedded in featureless valleys. Structures are difficult to track across the area. The southern part is tightly folded, with few clearly recognizable anticlines and synclines, but structural components can easily be traced for tens of miles.

Fieldwork in the northern part, in the spring of 1988, supported much of the interpretation of the remote sensing analysis. For instance, the indication from radar analysis that most, if not all, of the anticlines in the northern part of the study area were overturned – which was never recognized before – was proven by the field survey.

The combination of remote sensing and fieldwork proved invaluable in understanding the fold belt tectonics better and aided considerably in interpreting the offshore seismic and in the decision making process regarding a drilling location.

APPLICATION OF SYNTHETIC APERTURE RADAR TO
GOLD EXPLORATION IN TROPICAL REGIONS

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SUMMARY

Gold exploration in tropical regions is frequently made difficult by the presence of heavy jungle coverage that restricts access to the area and by the lack of adequate map coverage. Remote sensing can provide methods for addressing these issues, but other factors such as frequent cloud cover can inhibit attempts to survey remote regions using conventional airborne techniques. Recent efforts in SE Asia have demonstrated the usefulness of airborne synthetic aperture radar to acquire important data in a timely and cost-effective manner. Comparison of SAR data from SE Asia with both satellite imagery and aerial photography shows that important features often appear in the SAR that are not apparent in other data types. A case study from Central Kalimantan is presented that illustrates both the technical and financial benefits of using airborne SAR techniques.

RECOGNITION OF GEOLOGICAL FEATURES IN AIRBORNE SAR IMAGES

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SUMMARY

In geological exploration from remotely sensed data, the identification of rock units takes an important role. Because of their wealth in textural information, images from a Synthetic Aperture Radar, SAR, can greatly contribute to the recognition of geological features and to geological remote sensing in general.

Texture is the term used to describe a surface phenomenon in an image. It has been shown to be a significant feature which is useful in SAR image analysis. Traditionally, texture analysis for SAR image interpretation has been performed mainly at a visual level, i.e., the geological features are identified manually, except for some limited linear extraction tasks that could be automated.

The purpose of this paper is to introduce a new approach to texture analysis for the automatic identification of geological features in remotely sensed images. The method used in our study was termed the "Texture Spectrum" approach. In it, an image is decomposed into a set of Texture Units. Each unit may be considered as the smallest complete one that best characterizes in a square raster the local texture in the eight directions from a given pixel. The image may then be described by the characteristics of its Texture Spectrum. In the domain of such spectrum, several analyses can be easily performed that lead to textural pattern recognition, e.g., feature extraction, filtering, enhancement, segmentation, etc.

This paper provides application examples of the new method to airborne SAR images in Precambrian terrains in the Northwest Territories of Canada. The data were acquired during October 1987 by the aircraft of the Canada Centre for Remote Sensing. The vegetation in the study area is a typical tundra; however, it includes the extensive coasts of Bathurst Inlet. In the area, a mineral potential evaluation by the Geological Survey of Canada was performed to assess its suitability for a national park. Because of its geological and metallogenic interest, a detailed mapping of part of the area has been planned for 1989. A multiple data set of remotely sensed images was constructed that also included digital data from geological, geophysical, and topographic maps. In particular, four strips of airborne SAR imagery of 4096 x 20000 pixels of

size 4 x 4 meters have been recorded over the area. From those, several subimages were extracted to cover areas of particular interest in geological exploration. In such areas, different metasedimentary rock units, massive to foliated granitic intrusions, gabbro bodies, and diabase dykes have been mapped at a reconnaissance level. Over each unit, image samples of 40 x 40 pixels were selected to compute texture measures for rock discrimination. Traditional Haralick's features, such as Angular Second Moment, Homogeneity, Contrast, Entropy, Correlation, Dissymmetry, and Chi-Square were computed as well as three newly proposed textural features, Black-White Symmetry, Geometrical Symmetry, and Directional Degree, which are derived from the Texture Spectrum. The results show that such a spectrum has a greater discriminating performance on SAR images than the more traditional methods mentioned above. The selected rock units can all be easily distinguished by the three new features proposed here.

The textural transformation, that requires scanning the SAR image by a window, and calculating the textural measures for every position of the window, can provide several textural images from an original scene. Generating such multi-dimensional data for a decision space can be useful in the automatic recognition of geological features, geological exploration, and the interpretation of other remotely sensed images. Several enhanced images can be generated in map-form to assist in planning a detailed geological mapping survey.

A MULTI-FREQUENCY POLARIMETRIC SAR
FOR REMOTE SENSING AND ITS APPLICATIONS

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SUMMARY

A fine resolution tri-frequency fully polarimetric multi-mode SAR has been developed by ERIM, in conjunction with the Naval Air Development Center (NADC). The SAR, installed aboard a Navy P3-A, and proven to be highly reliable, can map up to 3000 sq. miles an hour for up to 8 hours. The system can transmit and receive, in up to four channels, any one of three frequencies (X, C, or L-Band) either horizontally or vertically polarized pulses. Each channel is completely independent and thus the system can be operated in a multi-frequency mode (X, C, and L bands transmitted simultaneously) or a full polarimetric mode (all rectangular polarization combinations, i.e. HH-HV-VV-HV, of a given frequency collected simultaneously). The number of channels can be decreased from four to two or one, trading frequency and polarization diversity for increased swath coverage. The fine range resolution can also be traded for increased swath coverage.

ERIM is just beginning to apply the principles of radargrammetry to radargraphs obtained with the P3 SAR to perform stereometric mapping. Stereometric mapping from radargraphs will provide a new dimension to topographic mapping which will enhance the normal contour map rendition with shading from the SAR image itself. The three dimensional impression of the relief obtained in this way can be exaggerated by producing stereo-mates of the shading for stereoscopic viewing with conventional pocket or mirror stereoscopes. This kind of mapping will be a great benefit to geologists for geologic structure analysis.

ERIM is also completing the polarimetric calibration of the system, which, when completed, will allow further research into the polarimetric discrimination of crops, foliage, and terrain types. Polarimetric discrimination involves the comparison of the relative phase differences of the radar return signal between differently polarized images. Several data sets over forested areas and cropland have begun to be examined. This information might be useful to a geobotanist analyzing the occurrence of stressed vegetation in an area due to the mineral composition of the soil.

The P3 SAR has completed several data collections, including a major collection of multi-frequency data over the Marginal Ice Zone in the Arctic Ocean, which produced large mosaic images of the ice floes as a simulation of the data to be obtained by the ERS-1 SAR satellite scheduled to be launched next year. The application here would be the aid of site selection (and evacuation) of oil drilling platforms and the monitoring of nearby sea lanes.

CANADIAN RADAR PROGRAMS - AN OVERVIEW

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SUMMARY

There are three main Canadian programs concerned with radar remote sensing. The first is concerned with the establishment of a Canadian ground segment to receive and disseminate data which will be available as a result of the Canadian participation in the ERS-1 Program of the European Space Agency. The second, called Radar Data Development Program, is primarily concerned with the establishment of applications of radar data, such as in geosciences information extraction. The third, called RADARSAT Program, is concerned with the development of the first earth observation satellite for Canada. One objective of RADARSAT will be to acquire global Synthetic Aperture Radar stereo-data. These programs and the interrelationships among them are summarized.

**REMOTE SENSING APPLICATIONS TO NEOTECTONIC
STUDIES IN SOUTHERN ONTARIO**

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SUMMARY

The Ontario Geological Survey is conducting detailed geological investigations of possible neotectonic features in Prince Edward County, southern Ontario. For the purpose of the study, neotectonic has been defined as any movement of the bedrock that occurred post-glacially, or within the last 8 to 10 thousand years. These recent bedrock movements can be identified by disruption of the overlying surficial deposits thus making remote sensing techniques particularly useful for neotectonic studies.

A program was initiated to map both surficial and bedrock features in the Prince Edward County. A series of false-colour infrared air photographs were flown by the Ontario Centre for Remote Sensing in the spring of 1986 at a scale of 1:10,000. Ground observations were made of interesting tonal patterns and lineaments identified on the air photographs during the summer of 1987. The resolution of smaller features on the photographs was poor and a second series of air photographs were flown at a scale of 1:2000 in the fall of 1987. The patterns on the air photographs were found to represent a variety of natural and man-made features.

Important bedrock features include: faults, joints, open crevices, folds, buckles and pop-ups. The western part of the study area is cut by a northeasterly trending fault which is the southern arm of the Picton Fault System. Many of the larger bedrock structures, such as pop-ups, occur centrally in the study area and are in a zone oriented perpendicular (northwesterly) to the fault. The structures within this zone also trend in this direction.

Of significance in the surficial deposits are: long linear depressions which have similar orientations to the underlying bedrock structures, and abandoned beaches that are cut and/or gapped by linear trends also related to the bedrock structures. The distribution of disturbed surficial deposits also indicate the existence of the central zone, noted above, where there is a high frequency of bedrock-related linear features.

Preliminary investigations indicate that geological processes have produced a complex inter-relationship between bedrock structures and Quaternary deposits. The structural features

described above may be the result of rejuvenation and modification of older zones of weakness by glacial, post-glacial and ongoing geological processes.

The presence of pop-ups, other stress release features, and neotectonic features in southern Ontario has important implications for the construction of environmentally sensitive structures. A clear understanding of these features, the stresses which formed them, and their future behaviour will permit an accurate assessment of potential construction hazards.

In addition to evaluating neotectonic occurrences, the study provides detailed geological information necessary for the testing and interpretation of remote sensing techniques. A number of these techniques have been or are scheduled to be applied to this area including airborne "C" and "X" Band SLAR and SPOT Image.

GROUND PENETRATING RADAR FOR SUBSURFACE ENVIRONMENTAL APPLICATIONS

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SUMMARY

Ground penetrating radars (GPR's) are a class of remote sensing radars operating at sufficiently low frequency that energy can be transmitted through many metres of earth, thereby permitting, in principle, the imaging of subsurface features. Operating frequencies of a few tens to a few hundreds of megahertz are typically used, and transmitted pulse lengths of a few nanoseconds are attempted to achieve adequate range resolution. Subsurface reflections are obtained from discontinuities in the electrical properties of the soil, including those often associated with the water table, with geological features, or with subsurface contaminants.

The interpretation of GPR data has proved to be very difficult. Ranging is difficult because the velocity of propagation is dependant upon the electrical properties of the material. The low frequencies involved make it difficult to achieve a focussed beam, with adequate azimuth resolution. The real problem, though, involves correlating the returns from the radar with measured electrical properties from beneath the surface, and in making an interpretation involving the important geological and environmental characteristics in the area.

Some progress has been made in the utilization of GPR for environmental and geological monitoring. First, modern radars have been developed that utilize digital sampling and recording systems. Second, the availability of digital data sets has allowed the application of a variety of digital signal processing techniques. Most recently, a variety of tools initially developed for the processing of seismic data have been modified and applied to GPR records. Spectral processing, deconvolution, and migration have all yielded results which improve the interpretability of data.

Some experiments involving the development of an "expert system" interpreter for GPR data have been conducted.

This paper describes the application of GPR to the detection of subsurface contamination by hydrocarbons and to the mapping of brine spills near producing oil wells. The application of seismic processing techniques to these data sets is shown, and physical models are presented to describe the character of the radar data. Finally, a development plan is described which will take GPR from an experimental system to an operational tool, that can be applied to problems involving environmental monitoring and geologic investigation.

PUTTING SPECTRAL VALUES IN THEIR PLACE - A PRIVATE
CONSULTANT'S EXPERIENCES WITH DATA INTEGRATION METHODOLOGIES

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SUMMARY

The Author would address the conference in his capacity as a photo interpreter, image analyst & teacher in the interrelated disciplines of applied land geoscience & from a background of 30 years full-time practice including 14 years of providing terrain assessments as value-added products in the commercial market, contributing to projects on five continents.

My proposed presentation is motivated by my strong experience that spectral data are but one of a number of evidential factors that must be combined to reliably identify & characterize many biophysical earth surface features.

The energy & matter interaction processes of such features are spatially and temporally multi-dimensional and many of these are poorly or only indirectly related to the features' reflectance/emittance properties. For many types of analyses pixels can remain as mixels, and the separation of component signals, so desirable elsewhere, is less critical.

My ideas concerning the proper place of spectral values in land geoscience information extraction techniques will be expressed by viewing them within the unifying principle of the term INTEGRATION as it relates to such remote sensing (R.S.) concepts as:

- image analysis elements
- land systems as resource inventory mapping units
- background geobotany
- multistage approach
- sensor system resolutions

In the process, such relatively esoteric terms as INVERSION ALGORITHMS and SYNERGISM, will be viewed from the perspective of qualitative data analysis techniques.

For the benefit of those attending who are just becoming familiar with R.S. technology, this perspective will be developed into a restatement of the role & ongoing value of such techniques in the particular fields of civil and environmental engineering.

In addition to these applications, the presentation will be relevant to such other conference topics as:

- photogeology & image interpretation
- geological hazards

- exploration & mapping in glaciated terrain
- R.S. in vegetated terrain

Two case studies will be presented as examples of efficient, although time & cost constrained, applications of the advocated integration & analysis techniques.

The first case consists of a regional scope (25,000 km²) large scale (1:50,000) soil resource inventory in Indonesian New Guinea, a forested humid tropical environment.

The second case involves a national scope (475,000 km²) medium scale (1:200,000) land cover, land use inventory encompassing a range of latitudinal bioclimatic environments in Africa (Cameroun).

THE EXXON-VALDEZ OIL SPILL, ALASKA

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SUMMARY

Remotely sensed data and shipboard measurements have been collected of the Exxon-Valdez Oil Spill after the tanker ran aground on Bligh Shoal, Alaska, 24 March 1989. Over 10 million gallons of crude oil has circulated throughout Prince William Sound and the Gulf of Alaska from this spill. Satellite imagery, airborne imagery and observations, and shipboard measurements are being acquired to monitor the position, extent, and effect of the oil on this marine environment. This paper primarily concentrates on satellite analyses of the spill but will incorporate airborne data and shipboard measurements to support the interpretations.

Satellite imagery obtained by the NOAA Advanced Very High Resolution Radiometer (AVHRR), the Landsat Thematic Mapper (TM) and the SPOT Multispectral Scanner (MSS) have been analyzed to help ascertain the effects of the spill on the environment and its circulation along the Alaskan coast. The digital satellite data have been analyzed using image processing systems to emphasize spectral responses that may be related to oil on the water surface and on beaches along the coast. Turbidity and sea surface temperature (SST) are also being displayed to provide information on the circulation and distribution of surface water bodies.

US Coast Guard Side Looking Airborne Radar (SLAR) and visual aerial observations were used by NOAA to monitor the distribution and location of the spill, and to compile daily maps. Physical and biological effects are also being investigated in the field by research teams from the University of Alaska Fairbanks using the research vessel, Alpha Helix. Field Measurements include temperature, salinity, and chemical analyses of the water column. These field data have been incorporated into the analysis of satellite imagery to quantify interpretations.

The satellite data have not provided a distinct, single map unit that can clearly be identified as the oil spill. Instead various features seen on several data sets and in various wavelength bands appear to be related to large or concentrated patches of oil. On AVHRR thermal infrared imagery the leading portion of the southwest-circulating spill coincides with radiant temperatures that were 1.5 to 2°C cooler than surrounding water. The relatively cooler radiant temperature of

the oil compared to that of the water would require a 2 to 3% difference in the emissivity between oil and water. The thermal AVHRR (and presumably TM) delineates surface isotherms whose geometry is similar to that of the oil spill as observed in the airborne data and hence the gross trajectory and distribution can be inferred.

On SPOT MSS data ropey structures were observed in the water that coincide with similar structures observed by airborne observers. The distribution of these structures agree with the extent of the oil mapped from the airborne data. TM data have not yet been analyzed, but we expect to have results to present at the symposium. Overall the airborne SLAR data appears to be the best source of information on the distribution of the oil. This observation suggests that the SAR satellites to be launched in the 1990's may be a valuable source of information regarding oil spills.

REMOTE SENSING TECHNIQUES USED FOR SAND AND GRAVEL
EXPLORATION BY THE ALBERTA GEOLOGICAL SURVEY

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SUMMARY

During the last twenty years the Alberta Geological Survey (AGS) has routinely used Airphoto Interpretation (API) and ground resistivity (EM) techniques and has evaluated Landsat TM Image Analysis (TM), Synthetic Aperture Radar Imagery (SAR), and airborne resistivity (EM) for sand and gravel exploration. The overriding impetus has been to improve predictive capability while maintaining or reducing costs. Sand and gravel resources are mapped at three levels: a reconnaissance level (1:250 000 scale) to delineate potential areas for land use planning; at a detailed scale (1:50 000) to delineate deposits and estimate quantity and quality of materials for reconnaissance exploration and at a development level to prove reserves and quality. Each remote sensing method used by the AGS has been assessed to determine its application in terms of scale of investigation, depth of penetration, and predictive reliability. Traditional (API) is the primary remote sensing technique used in the inventory of and exploration for sand and gravel (aggregate) resources. Although API can be used at any scale of investigation the cost of the photos and the time to interpret them can be excessive for very large areas. Landsat images analysis and selective API can be used with existing surficial and geological maps at low cost for very large areas and reconnaissance studies. In areas where API and Landsat images are likely to provide little information because of lack of relief and deposit burial airborne EM can be an effective but costly way to explore for deposits at depth over large areas. Detailed mapping is best done with API followed by subsurface testing (drilling and trenching) and lab analysis. Areas with poor access for drill vehicles be studied with SAR or airborne EM to supplement API. SAR is particularly useful when merged with Landsat images (SAR - TM) as was done in the Fort McMurray area. Drilling and trenching is done on 100 m or less grids for development scale studies. Initial site analysis and later fill-in data (between drill holes or test pits), for deposit delineation, depth and overburden survey, can be provided cheaply and effectively by using ground EM units such as the EM-31 and EM-34. Remote sensing capabilities are improving and becoming cheaper but have already become established techniques in the search for aggregates in Alberta.

USING REMOTELY SENSED BOTANICAL INFORMATION
IN GEOLOGICAL EXPLORATION: ANTICIPATE THE UNEXPECTED

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SUMMARY

In moist temperature environments where deep chemical weathering has occurred, soils and supported vegetation can cover the parent materials and thus hinder geological mapping and exploration both in field and, particularly, from a remote sensing platform. Well developed soils in such environments are, however, very much a product of parent material and as such, support different plant distributions.

Such botanical information can be utilized not only as a reconnaissance exploration tool, but as part of a multidisciplinary approach at all levels of the exploration process. Researchers have documented how to separate, isolate, or even diminish the botanical component of remotely sensed spectral information in partially vegetated terrain. The work discussed here, however, deals with exploration in regions of total forest canopy cover as often found in mesic environments.

Thematic Mapper Simulator (TMS) data were collected over a previously studied area in southcentral Virginia containing regions of sulfide mineralization of copper, lead, and zinc in anomalous but non-lethal concentrations. Under such conditions, there is no change in percent canopy closure. Multi-year spring, summer, and fall data were collected using a NASA C-130 at altitudes between 2-7 km. These digital data were obtained and coregistered to geologic, topographic, soil geochemical, ground-based remote sensing (TM bandwidths), and botanical datasets.

While ground-based leaf spectral information from previous studies by our group was highly correlated with soil geochemistry, and successfully delineated the geochemical anomalies associated with sulfide deposits, at the location used in the present study there was no positive correlation between such leaf spectra and the aircraft vegetation spectral information. Leaf

spectral information was based upon one genus (Quercus) and primarily from one species, Quercus alba (white oak), one of the canopy dominants in the study area. White oak is relatively more sensitive to edaphic conditions than the other canopy dominants and hence the reason for the success of the ground-based work. This same sensitivity in white oaks, however, contributed to a reversal of expected seasonal spectral patterns associated with soil mineralization when aircraft data were examined. The spectral response observed in the aircraft data can be explained by species assemblage patterns. For example, conifers and hickory were more important over the mineralized areas, thus creating a definite association between canopy reflectance and soil chemistry. In addition, summer aircraft data had the strongest discriminating power, thus differing from the previous lab work by our group in a Quercus spp. dominated forest containing copper, lead, and zinc mineralization, where mineralized zones were most easily detected in data collected in the spring and fall.

This study demonstrates that the technique used to delineate mineralized areas in ground-based remote sensing data is not automatically applicable to aircraft-collected data wherein differences in spectral response over metal anomalies are strongly associated with canopy species composition. This can overshadow changes in leaf reflectance within a single species and, thus reemphasizes the importance of knowing what the remote sensing data are sensing, or, more formally, the importance of sampling design.

SPECTRAL REFLECTANCE RESPONSES
FROM LICHENS SUBJECTED TO METAL-INDUCED STRESS

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SUMMARY

Remote sensing using spectral reflectance from vegetation is becoming increasingly important in analysing stress in vegetation. Lichen carpets form an important component of the ground vegetation in northern Canada and may respond to metal stress such that they may be an aid in mineral prospecting. Caribou or Reindeer Lichen (*Cladonia mitis* Sanst.) mats were exposed to 0, 20, 40, 60, 80, 100, or 200 $\mu\text{g/g}$ copper sulphate for one hour and the spectral reflectance measured at intervals over the following 10 days. Measurements were made with a Barringer Hand Held Ratioing Radiometer (HHRR) at 0.650, 0.680, 0.700, 0.713, 0.733, 0.743, 0.753, 0.782, and 0.800 μm , i.e., at wavelengths corresponding to the filter set in the HHRR. Since arrangement of the podetia (lichen stems) in the mat and degree of wetness of the lichens were important contributors to lack of consistency in the measurements, their effects were minimized in the experimental protocol for measuring reflectance.

Copper exposures in excess of 20 $\mu\text{g/g}$ resulted in statistically significant spectral shifts of 2-3%. There was a gradual decrease, over a period of about 4 days, in reflectance values in both the red and near infrared regions. These copper treatments resulted in approximately five times the exposure levels of copper in the lichen tissues. Surprisingly, there were differences in response in *Cladonia mitis* and in *Cladonia rangiferina* (L.) Wigg., a near relative. In *Cladonia mitis* there was no visible colour change after exposure to copper as was seen with *Cladonia rangiferina*. However, exposure to cadmium or nickel resulted in a browning of the *C. mitis* podetia.

SPECTRAL RESPONSE OF VEGETATION TO METALLIC ELEMENTS
IN NORTHEASTERN MINNESOTA
USING HIGH-RESOLUTION AIRBORNE SCANNER DATA

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SUMMARY

High resolution airborne scanner data were acquired over a heavily vegetated region in northeastern Minnesota. The Geophysical Environmental Research, Inc. (GER) 63-channel airborne imaging scanner* was flown in early September, 1988, over areas of both known and suspected mineralization in a structurally complex, glaciated region. The Vermilion Fault study area, in an Archean greenstone belt, is being actively explored for gold. This area was covered by a single flight line about 21 by 8 kilometers. The second, larger study area in the Duluth Complex required two lines for coverage of a 40 by 8 kilometer swath. The primary site of interest in this area contains known copper-nickel deposits, but other sites covered by the flight include suspected copper-nickel deposits and copper-nickel-palladium-platinum-gold-silver prospects.

The study areas are covered by boreal forest and marsh and bog vegetation. Many plant species found in boreal forest regions are known to concentrate heavy metals. The presence of heavy metals in the soil is known to cause vegetative stresses that lead to morphological effects (stunting and reduced biomass) and species distribution changes. In addition, in greenhouse, field, and airborne data sets, spectral changes have been observed in plants growing in anomalous concentrations of metallic elements. Among the changes observed in laboratory spectral of greenhouse-grown metal-dosed plants are a shift to shorter wavelength (the red edge shift) in the long-wavelength edge of the chlorophyll absorption band centered at 680 nm and increased reflectance in the 550-650 nm region (the green reflectance peak).

The scanner is a new instrument with the high spectral and spatial resolution needed to detect the subtle spectral changes that indicate the early effects of metal-induced stress. We are comparing data from mineralized and unmineralized sites using image interpretation and spectral analysis techniques to identify the best channels, ratios, and channel combinations for minerals

* Use of trade name is for descriptive purposes and does not imply endorsement by the U.S. Geological Survey

exploration and environmental monitoring purposes. Waveform analysis using the Chebyshev polynomial method has enhanced our ability to detect the red edge shift in other data sets. These transformations were also performed on the GER data, and we are analyzing the results to detect the red edge shift.

Use of higher resolution instruments and subsequent specialized data analysis techniques offers the potential for more effective mineral exploration in heavily vegetated regions. These methods may also be useful for examining environmental conditions in forested areas.

**REFLECTANCE ANOMALIES OF HARDWOOD FOREST COVER
ABOVE LEAD-ZINC CONTAMINATION**

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SUMMARY

Contaminants such as base metals and hydrocarbons can cause physiological distress in plants which then appear as spectral anomalies in the typical reflectance curve of chlorophyll-bearing vegetation. The development of high-resolution narrow-band airborne sensors permits signatures of stressed vegetation to become a potentially valuable tool for mineral exploration.

At a Canadian site, on the Shield in Eastern Ontario, ground and airborne spectral data were tested against geochemical anomalies in soil and bedrock, and against leaf ash chemistry of various species in a hardwood forest cover. The site, in the Great Lakes Forest Region, comprises thinly (<3m) drift-covered Precambrian bedrock overlain by Paleozoic shelf carbonates both of which are cut by Pb-Zn-Ba-Sr veins.

Ground spectral data of mineralized vegetation showed distinct changes in reflectance at the green reflectance peak (570 nm), the chlorophyll absorption maximum (680 nm), the red reflectance edge (680-750 nm), and at the infrared reflectance shoulder (750-1100 nm). Changes vary in amount and diagnostic spectral position with tree species. They are most marked in sugar maple, trembling aspen, and white birch.

Leaf ash chemistry shows some species are metal-tolerant and that spectral change is not always proportional to biogeochemical change.

Narrow-band spectral data from two Canadian airborne sensors (MEIS II and MONITEQ PMI) were calibrated against ground spectral data and the imagery enhanced. A regional overprint of stress related to cultural effects is seen in all species at 680 nm in PMI images. Intense stress in trembling aspen, white birch, and maple of various ages appears at 570 nm, 680 nm, and in the 680-750 nm range on MEIS II imagery.

Given a spectral library of common forest trees, it will soon be possible to image stress distribution in a canopy of known species composition. As regrowth species (trembling aspen, white birch) are sensitive indicators of stress, the technique can be applied to cut-over areas as well as to primeval forest stands.

A GROUND-BASED SPECTRAL STUDY OF VEGETATION
IN THE SPRUCE-FIR FOREST, MT. MOOSILAUKE, NH

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SUMMARY

This study analyzes ground-based spectral data of foliar samples collected from trees growing within the northern spruce-fir forest to evaluate the relationships among sensor bandwidth, spectral reflectance, and geobotanical parameters such as elevation, species type, and estimates of vegetation damage. Spectra of the leaves or needles of heart-leaved paper birch, balsam fir, and red spruce were measured from samples collected on Mt. Moosilauke, New Hampshire during August 1987 and July 1988. The spectra of red spruce samples collected from trees with different degrees of visible crown damage based on estimates of needle loss and chlorosis were also measured. The results discussed below are from samples with leaves or needles still attached to branches because these samples more closely represent the canopy seen by the satellite.

High resolution spectral data (~2.8 nm bandwidth) in the 458-1066 nm region were measured with Spectron Engineering's SE590 spectroradiometer and reduced to 41 bands (~15 nm bandwidth) by averaging. In addition, both the wavelength and percent reflectance values of the green and red absorption minima, the green reflection maximum, and the red edge were determined by analyzing the running average in ~10 nm bands. Along with these relatively narrow-band spectral data, broader-band spectra were measured with Barringer's Hand Held Ratioing Radiometer (HHRR) in the 6 visible and near infrared TM bands (60-270 nm bandwidth), in 3 bands along the red edge (20 nm bandwidth), and in one band at 1260 nm (20 nm bandwidth). A correlation analysis was performed using these spectral and geobotanical data.

With the ~15 nm SE590 spectra, all species show a decrease in reflectance with elevation, with the highest correlations ($\geq 95\%$ confidence) at about 464 nm, 664 nm, and from about 768 to 893 nm across the NIR plateau. In the 10 nm SE590 spectra, decreases in reflectance are also seen in the blue and red absorption troughs and at the inflection point of the red edge ($\geq 95\%$ confidence). This relationship is also seen in the 20 nm HHRR band centered at 670 nm, but is not seen in the HHRR TM3 band (60 nm bandwidth) centered at 660 nm.

Both broad-band (60-270 nm bandwidth) and narrow-band (20 nm bandwidth) HHRR spectra as well as narrow-band (~15 nm bandwidth) SE590 spectra of red spruce have no significant correlation with estimates of visible crown damage based on needle loss and chlorosis. However, the highest resolution (~10 nm bandwidth) SE590 spectra have a significant direct correlation ($\geq 95\%$ confidence) with needle loss in the red chlorophyll absorption trough in the

visible spectrum. There are no significant correlations between needle loss, chlorosis, and NIR reflectance or the position of the red edge.

The red edge appears to be species dependent with conifers having a mean red edge position at 717 nm and hardwoods having a mean red edge position at 712 nm. The apparent shift of the red edge towards shorter wavelengths for hardwoods relative to conifers indicates that care must be taken when interpreting high resolution spaceborne or airborne data collected over a mixed deciduous coniferous forest.

These results highlight the importance of narrow-band spectral data, especially in the visible region of the spectrum, for detecting vegetation damage based on needle loss and chlorosis. In addition, it appears that elevation has a role in influencing the reflectance properties of vegetation and that the position of the red edge is species dependent.

ESTIMATION OF SPOT ORBITAL PARAMETERS

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SUMMARY

The resolution, stereo, and multispectral characteristics of SPOT digital imagery offers many possibilities for deriving precise surface positional information. The pushbroom nature of the imagery, however, exhibits several geometric problems when attempting to resolve the instantaneous satellite orbital parameters. This problem is particularly difficult to resolve in the absence of adequate ground control information. Fortunately, in many cases, well defined terrestrial points are visible on stereo pairs of SPOT imagery. These points can be used as relative control information when resolving the orbital parameters. A solution is offered whereby both absolute and relative terrestrial information are incorporated into the formulation. The proposed formulation simultaneously resolves the orbital parameters of a stereo pair (or more) of images. The estimated orbital parameter values along with their precision and reliability information are computed during the solution. Statistical testing of this information permits the rejection of erroneous terrestrial data from the solution. Upon solving the orbital information, three dimensional coordinate information can be derived from the stereo imagery. Approximations for three dimensional coordinate determination are offered in the context of real-time processing. Selected test results are given as well as some suggestions for future research in this area.

DIGITAL STEREO DISPLAY AND MEASUREMENT

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SUMMARY

The French SPOT satellite provides both multispectral and panchromatic stereo with a respectable base-height ratio. However, much of the stereo interpretation of this data has been based on conventional analysis of photographic hard-copies of the imagery, losing much of the inherent value of the digital format. Various approaches to displaying stereo imagery on a CRT monitor have been developed. Each approach offers particular advantages and disadvantages in display size, color capability, visual quality, ability to zoom and roam the stereo image, mensuration, and compatibility with existing image processing systems.

We display stereo data with a system that alternates the left and right images on the screen at 120 Hz, to give 60 stereo views per second with no visible flicker. A combination of electronically switched LCD screen and passive polarized viewing glasses present the left and right images to the viewers' left and right eye, respectively. With the on-screen stereo, we are able to radiometrically and geometrically match the left and right images and apply tonal and spatial enhancements interactively to the stereo image.

In addition, we have developed a digital parallax bar to measure point elevations and dip and strike. Point elevation accuracies of 14 meters were achieved on images with a 0.7 b/H ratio. The accuracy of slope measurement is a function of point elevation precision, slope angle and slope length. Preliminary results indicate that dip measurements acceptable for photogeomorphic interpretation can be made in both low-relief and high-relief terrains using this technique.

The system is compatible with image processing systems operating on microcomputers, minicomputers, and workstations, and is a useful and effective addition to existing image processing capabilities.

REMOVAL AND ALTERATION OF TOPOGRAPHIC UMBRA AND SHADOW
IN LANDSAT TM IMAGERY OF MOUNTAIN AREA

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SUMMARY

LANDSAT images of hill and mountain areas are characterized by the sophisticated topographic shadows. Although the topographic shadows in images could show the geomorphological and geological relief features for image interpretation, they are one of the main impediments to the quantitative research of remotely sensed data, e.g., the information extraction of hydrothermal alteration in mountain areas and land-cover classification of remotely sensed images in relief areas, etc. Moreover, the constant solar azimuth in LANDSAT images is disadvantageous to image interpretation of geological structures in different directions. Therefore, it is necessary to study the removal and alteration of topographic shadows in LANDSAT TM images.

Most previous studies on the shadows in images were often to remove or depress the effect of the dark hillside which could not obtain the sunlight because the angle between the normal line of the hillside plate and the sun-ray is more than 90 degree. In the study, these dark hillsides have been defined to be the topographic umbra, and the different concept of the topographic shadow has also been defined. The topographic shadow in images is the area which was shaded from sunlights by hills, peaks or other higher objects, especially occurred in the images with low sun illumination in winter.

In the study, a model for removing the topographic umbra and shadow has been established upon the sensor response of the horizontal objects, the effects of both the sunlight and the sky scattered light, and the digital terrain model (DTM). An effective scanning method has been designed to discriminate the topographic shadow areas in the TM images. The sunlight coefficient in the model has been verified to be able to reflect five types of solar illuminations in mountain areas; the illuminated hillside, the half illuminated hillside, the dark hillside (umbra), the shadow area, and the level land. For the sky scattered light, its coefficient in the model, which was calculated from a modified sky scattered light model, could represent the different scattering features on peaks, ridges, and valleys.

In addition, the study involved the alteration of the solar azimuth and zenith angle. The alteration method for two different solar illumination TM images has been developed upon the intermediate of shadow-free image, so the original image could be changed directly into a new shadow image.

The results of analysis, classification, and field inspection for the processing TM image of the study area near Hangzhou city have shown that the object recognizability and classification accuracy in the processed image have been obviously improved. The altered images could provide various new features for image interpretation, and the methods presented in the study are more effective, feasible, and useful for the quantitative application of remotely sensed data.

AN APPLICATION OF PIXEL SWAPPING TECHNIQUE IN REMOTE SENSING

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SUMMARY

Pixel swapping is a technique for extracting particular patterns and features from images by shifting an image and performing an inter-pixel operation. Line information, branch points, and features can be easily extracted from images by this technique performing relatively easy operations. Complicated patterns can also be divided flexibly by selecting appropriate shift parameters and operation expressions. On account of its ease and flexibility this technique holds a good promise to find application in various areas, especially remote sensing in such ways as extraction of lineaments, water systems, branch points, and suchlike. At first, we studied this technique by using the artificial pattern. And then, we applied to extract the pattern information of SAR. At this conference, the authors will discuss the concept of pixel swapping, its technique, and pattern information extracting from SAR images as an example of its practical application, also referring to an image processing system to which is suitable for this technique.

A KNOWLEDGE BASED SYSTEM FOR DIGITAL IMAGE PROCESSING
FOR EARTH RESOURCES APPLICATIONS

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SUMMARY

Since the launch of the Landsat satellites in the early 1970's, digital remote sensing imagery has become an important data source for the identification and management of natural resources. Satellite imagery is popular for these applications, because it is collected continuously, thereby allowing repeat coverage, and because the images are in digital format suitable for computer processing. However, the large data volumes collected, especially by the newer, higher resolution satellites (Landsat TM and SPOT) must be processed in an efficient manner, e.g., through the integration of such imagery into geographic information systems (GISs), if remote sensing data are to be of any practical use.

While image processing tasks, such as registration, enhancement, and classification, have been automated, the interpretation of imagery (i.e., assignment of meaningful names to image classes) has remained a primarily manual and time consuming task, which requires considerable human expertise. Currently, not enough skilled personnel are available to interpret the imagery collected by earth resources satellites. This creates a bottleneck in the processing and analysis of digital imagery, which limits the usefulness of digital imagery for mapping tasks.

Image interpretation has not been automated because traditional (procedural) programming methods are suitable mainly for numerical computation and, in remote sensing, are therefore aimed at spectral pattern recognition. Image interpretation, however, apart from spectral information, requires analysis of spatial pattern and contextual information, and a considerable amount of experience and judgement calls on the part of the interpreter. This type of information is best automated in an expert system environment.

In the Department of Surveying Engineering at the University of Calgary, work is being carried out to develop a knowledge based system for the extraction of cartographic features from digital imagery. The aim of this research is to have the system mimic the processes involved in human image interpretation. This involves the description of feature using attributes such as size, shape, pattern, and contextual information. The system is aimed at recognizing hydrography, transportation, terrain, geology, and land-use features to the level of detail present in 1:50,000 maps. The prototype knowledge base is being developed by using production rules and is written in PROLOG, an artificial intelligence language. While it is unlikely that one specific set of attributes can completely describe any one feature, it is expected that a knowledge based image interpretation system will improve the consistency of image interpretations. When completed, the system will there facilitate the integration of remote sensing data into GISs and will assist in the efficient management of satellite image data.

USE OF A GEOGRAPHIC INFORMATION SYSTEM AND IMAGE PROCESSING
TECHNIQUES TO THE INTEGRATION OF REMOTE SENSING DATA AND DIFFERENT
GEOSCIENTIFIC DATASETS TO MINERAL EXPLORATION IN THE IGLESIENTE
MINING DISTRICT (SW-SARDINIA)

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SUMMARY

During the last years, Geographic Information Systems (GIS) and image processing techniques became important tools for a combined evaluation of remote sensing data and geoscientific datasets. The main topic of this case study is the application of these tools to an effective integration of different combinations of remote sensing data, structural, geophysical, and geochemical datasets into mineral exploration in the Iglesias lead-zinc mining district (SW-Sardinia).

The SW-Sardinian Pb-Zn-Ba (-Fe-F-Cu) ore deposits, which are estimated to belong to the Mississippi Valley Type, are bound to Lower Cambrian limestones and dolomites. They are strongly affected by Caledonian and especially by multiphase Hercynian tectonic. Partly occurs hydrothermal influence and contact metamorphism related to late Hercynian granite intrusions. The major orebodies, which range from syndiagenetic to epigenetic, are unevenly distributed within the ore bearing formation, and with the exception of their association to the sedimentary environment, no further definite hints to the ore facies have been described.

To define additional exploration criteria for a target area covering about 200 km² NW - SW of Iglesias, all available geoscientific datasets were examined and at last a variety of stream sediment geochemical, aeromagnetic, aerelectromagnetic, and structural (i.e. lineament density and tectonical maps) map data were chosen for further interpretation and combination with Landsat-TM and partly SPOT panchromatic data.

In a first step, the maps were digitized as polygon overlays using the input segment of a GIS and then converted to grid format. In the following classified combinations of the polygon, overlays were calculated within the GIS' management and manipulation segment and plotted as classified thematic maps.

Image processing techniques like contrast enhancement, spatial-filtering operations, and Intensity-Hue-Saturation (IHS) transformations were applied to the gridded data to improve their interpretability and to integrate them into thematic combinations with remote sensing data. In addition, ratioing techniques were applied to the Landsat-TM data to display limonitic surfaces as possible indicator for oxidized orebodies.

In our presentation, the characteristics and the advantages of the different integration methods will be discussed as well as the thematic value of the different combinations of datasets for mineral exploration in the test area.

As first concrete result, we can present a definite coincidence of structural and geochemical anomalies, which shows good correlation with known orebodies.

DATA INTEGRATION FOR GOLD EXPLORATION IN
EASTERN NOVA SCOTIA USING A GIS

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SUMMARY

The recent renewal of interest in gold exploration in the Meguma Terrane of Eastern Nova Scotia, Canada, has afforded an opportunity to compile and co-register a diverse digital geologic data set with the objective of producing gold potential maps to aid regional exploration activities.

Data analyzed include airborne C-band and radar satellite TM imagery, airborne geophysical (vertical gradient magnetics, gamma ray spectrometer), ground sampled geochemical data (lake, till, biogeochemical), geological maps, and mineral occurrences. All the data was co-registered and enhanced using an image analysis system and a GIS and spatial modelling of the data was accomplished using the GIS.

A consistent genetic model for gold genesis and deposition in the Meguma Terrane has not been fully developed and at present is under much discussion. However, a number of empirical observations regarding the spatial location of known gold occurrences and geologic features have been documented. Gold occurs primarily in bedding parallel (or slightly discordant) quartz veins within a specific lithological formation in close proximity to the axes of tightly folded anticlines. More recently, certain investigators have also made spatial correlations with granitic plutons, east-west trending shear zones, and younger brittle-ductile NW trending faults.

The objectives of this paper are to evaluate the remotely sensed data (radar, TM, geophysical) for defining potential gold bearing structures and then to use the observations discussed above to select geologic variables (i.e. significant geologic structures, geochemical "pathfinder" elements, gold bearing lithologies, etc.) thought to be significant for regional gold exploration. Spatial modelling of these geologic variables with respect to the known occurrences is undertaken using the GIS to produce gold potential maps.

The remotely sensed data was co-registered to a UTM corrected base map and combined using an IHS colour display technique to produce image products in which geologic structure is enhanced. These enhanced products were interpreted for geologic structures and geologically calibrated by comparison to geologic maps and through a reconnaissance field mapping program. The spatial significance of the geologic structural data and geochemical data were evaluated by statistically testing their distribution with respect to the known gold occurrences. Potential maps were constructed separately from the structural and geochemical data using a weighted and unweighted spatial modelling technique. These maps were compared using how well they predicted the known gold occurrences as a basis for comparison. Finally, a gold potential map was produced based on both the structural and geochemical data.

The predictive power of the potential maps were evaluated statistically, and it was found they predicted the spatial location of virtually all the known major gold occurrences. More importantly, they indicated areas of high gold potential where no occurrences are known to exist.

VREDEFORT OVERTHRUST - A TECTONIC STUDY BASED ON CO-REGISTERED
LANDSAT, GEOPHYSICAL, GEOLOGICAL, AND DIGITAL TERRAIN DATA

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SUMMARY

The Witwatersrand Basin of South Africa is the best-known of Archaean sedimentary Basins and contains some of the largest gold reserves in the world.

The Vredefort structure is situated in the center of the Witwatersrand basin which is defined by the present distribution of upper Wits sediments. On the northern and western sides, the Vredefort core is surrounded by a collar of steeply dipping and overturned strata. The nature of the southern and eastern margins of the Vredefort core is less well understood because of the Karoo cover.

Surface geology and field observations on the Archaean rocks, the Rim synclinorium, the Potchefstroom fault, the Spits syncline, the Black Reef deformation, and the Rand anticline, suggest a basement overthrusting origin for the Vredefort Dome during the post-Transvaal period. The pre-Ventersdorp paleosurface supports the Vredefort basement overthrusting origin and suggests a thrusting direction from SE to NW.

A data base system has built up including Landsat TM data, Surface and Subsurface geological data, Digital Terrain, and Geophysical data.

From the Correlation Matrix, high correlation and strong redundancy express the TM3, TM5, TM7 bands. Principal Component Analysis was carried out between these three bands in order to enhance subtle differences. PC3 revealed curvilinear features concentric to the Vredefort collar beneath younger Karoo sedimentary cover.

Shaded relief images (SR) have been derived from the Digital Terrain Data with sun azimuth 92° (Landsat TM's sun azimuth) and different sun elevations. Images with low sun elevations reveal curvilinear features concentric to the Vredefort collar. Most of the curvilinear features follow the drainage patterns.

Pre-Karoo geology has been digitised and combined with the PC3 and the SR indicating that drainage patterns are related to pre-Karoo geology following surfaces of weakness such as bedding contacts, fault, and thrust planes. The whole structure is concentric to the Vredefort collar from Welkom to Klerksdorp and to the NW.

An aeromagnetic vertical gradient image has been derived and many colour aeromagnetic images have been produced. Magnetic curvilinear features concentric to the Vredefort collar extend NW including the Klerksdorp and the West Wits Line goldfields. There is also a noteworthy NW/SE axis of symmetry extending centrally through the Vredefort structure. Overthrusting of the Vredefort basement to the NW follows the same direction. Also, four major magnetic lineaments symmetric to the Vredefort axis have been recognised. They enclose an area in which an imbricate zone can be found and give an indication of the area from where the Vredefort basement overthrust may originate. Gravity slope aspect, and gravity shaded relief images show that the Bethlehem gravity high could be a crustal upwarp bringing lower crust near the surface and this gravity high related to Vredefort's core gravity high and interpreted as the extension of the Vredefort overthrust to SE.

PC3 has been merged with the aeromagnetic image and the pre-Karoo geology and the resulting image highlights correlations between the geology and the curvilinear structures concentric to the Vredefort collar.

The Vredefort overthrust can accommodate thrust blocks of Witwatersrand strata outside the conventional basin in addition to hitherto undiscovered slices of gold bearing stratigraphy within or below an imbricate zone.

APPLICATION OF LANDSAT DATA IN PROSPECT DELINEATION AND
ROCK DISCRIMINATION FOR HYDROCARBON EXPLORATION IN THE
NORTHWEST TERRITORIES, DISTRICT OF MACKENZIE, CANADA

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SUMMARY

Structural features of prospect dimensions have been mapped on a regional to prospect size scale in the predominantly covered Interior Plains of the Northwest Territories. These surface anomalies are the expression of subsurface structures with prospective merit as potential hydrocarbon reservoirs. Petro-Canada's Tweed Lake Prospect with the sandstones of the Lower Cambrian Mount Clark Formation as primary objective, is chosen as an example.

Rock discrimination using Supervised Classification has been tested and applied in two image portions of Landsat MSS and TM data, digitally processed from CCRS tapes at the Alberta Remote Sensing Centre in Edmonton. The reflectance pattern of mapped and well exposed outcrops has been determined, a distinct colour designated and applied to surrounding areas with promising results.

Pattern recognition from Landsat imagery, involving lineaments, drainage, and tonal anomalies and its geological interpretation on a regional to prospect size scale, has proven a valid lead for the prediction of geological subsurface features with prospective merit. The geological interpretation is supported with an acceptable degree of confidence in the light of more definitive data, such as outcrop control from published geological maps, regional Gravity and Aeromagnetics plus seismic surveys. The strong Tweed Lake tonal and drainage anomalies, supported by seismic data, have been verified by the drilling of the PCI Canterra Tweed Lake M-47 wildcat and the subsequent PCI Canterra Tweed Lake A-67 well as a significant gas discovery.

REMOTE SENSING DETECTION OF HYDROCARBONS AND HYDROCARBON SEEPS

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The spectral reflectance properties of Athabasca tar sands in the 0.35-2.6 μm wavelength range were examined because of their potential importance for remote sensing detection of surficial hydrocarbon seeps. The data are also useful for attempts to develop reflectance spectroscopy into a rapid, non-invasive analytical tool for the characterization of tar sands, heavy oils, oil shales, coals, and other hydrocarbon-bearing materials.

A common initial step in hydrocarbon exploration is the examination of available remote sensing data. The emphases at this stage has all too often been on the surficial structural geology. Potentially useful geochemical and mineralogical information is generally ignored, perhaps due to the fact that the spectral reflectance properties of many geological materials are poorly known. The spectral properties of tar sands were examined in order to provide laboratory data of use to remote sensing data analysis. Tar sands were selected for study because they are compositionally, and perhaps spectrally, very similar to oxidized hydrocarbon outcrops.

The laboratory-derived reflectance spectra of tar sands show an abundance of diagnostic absorption features in the 0.35-2.6 μm interval. Discrete absorption bands due to clay, water, and bitumen/organics appear at well-defined wavelengths. The strengths of the absorption features are directly related to the various phase abundances. The primary absorptions bands due to the hydrocarbons appear at $\sim 1.7 \mu\text{m}$, and from 2.3 to 2.6 μm . Clay absorption bands are found near 1.4 and 1.9 μm . These bands are attributed to bound and structural water in the clay structure and the wavelength positions of the band minima are diagnostic of the particular clay(s) present. The shape and broadness of these bands is also a function of the degree of crystallinity of the clay and the number of distinct structural sites available to the water and OH molecules. Absorption bands due to free water (unattached to the clays) are also present near 1.4 and 1.9 μm , but differ slightly from the wavelength positions of the clay bands. These differences are easily resolvable in moderate resolution spectra.

The laboratory data suggest that ~ 4 wt. % bitumen is required in a sample to be unambiguously detected. This detection limit will of course vary somewhat depending on the nature of the other phases present in the material. The 1.7 μm absorption band is potentially very important for remote sensing because it lies outside the regions of atmospheric absorption and is not significantly overlapped by the most common mineral absorption bands. The spectral slope in the 2.3-2.6 μm region can also be used for hydrocarbon detection. A negative slope characterizes all known clays, while a positive slope is present in the spectra of bitumen-rich (> 10 wt. %) samples.

Many organic-rich materials show certain broad spectral similarities to the tar sands-low overall reflectance, an absorption near 1.7 μm , and a positive slope towards longer wavelengths. While these spectral parameters are by no means unique, they can be used to severely constrain the possible compositions of a target when only very low resolution spectral data is available. As the capabilities of terrestrial remote sensing platforms improve, particularly with the upcoming EOS program in the 1990's, detailed laboratory spectral data must be available to effectively analyze the information which will be obtained.

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UTILIZATION OF LANDSAT TM TO IMPROVE MAPPING OF THE NIGER DELTA

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SUMMARY

Multispectral satellite images of the Niger Delta are being digitally integrated with company CAD (computer-aided drafting) base maps by Chevron Overseas and Gulf Oil Company of Nigeria to efficiently update a wide variety of geologic and cultural features critical to exploration and development. Imagery provides a unique and up-to-date overview of petroleum activity, geomorphology, and human expansion across the delta. Geologic and cultural features updated with imagery include delineation of 1) coastline and rivers, 2) nearshore "bathymetry", 3) channels and canals, 4) onshore well locations, 5) offshore gas flares, 6) terrain/vegetation conditions, 7) urbanizations.

Atmospheric conditions are severely degraded because of airborne dust associated with "Harmattan" during the season of minimal cloud cover. Landsat TM imagery was selected as the optimum satellite sensor for this project primarily because the reflected near-IR bands (4, 5, 7) displayed minimum degradation in comparison with visible bands 1, 2, and 3. Visible bands suffered a major loss of resolution, even on images with apparent minimum airborne dust. In addition, the resolution of TM bands 4, 5, and 7 was adequate for visual detection of individual well sites, enabling rapid and accurate digital registration of the vector CAD file (containing well locations as Lat/Long points) with the raster TM image. TM's usefulness is significantly improved by registration with an existing CAD map.

Landsat TM reveals extensive changes (and errors) in the shape and location of the delta's coastline and river system as compared with the CAD map. The CAD map was derived from 1950's air photo mosaics. Bathymetric mapping is limited because coastal waters are loaded with silt, severely limiting penetration of water by short wavelength visible light. Nevertheless, numerous uncharted shoals and spits were detected with TM. Beach deposits, zones of breaking waves, and shoals were able to be classified as unique features.

TM bands 4, 5, and 7 clearly delineate a complex system of natural and man-made channels across swampy terrain that is not available on the CAD map. These channels are often dredged to create drilling sites. When the CAD map (with its well symbols) is embedded into the Landsat image, a highly informative, up-to-date waterway map is generated. In addition, the embedded CAD file permits plotted locations of onshore wells to be verified. Offshore wells are not readily apparent on the imagery; however, their locations are provided by the CAD file. The plotted CAD file enables correlation of offshore gas flares (recorded by TM) with offshore fields.

Mangrove swamps are extensive and pose special operational problems. TM band 4 (as expected) provided the most information within the mangroves by clearly delineating the land/water contact and providing the most detail about vegetational changes. On upland and drier portions of the delta, the effects of a rapidly expanding human population are best captured with TM band 7. Roads, villages, urban centers, and clearings are highly reflective in band 7. Such information, plotted in the correct geographical location, is essential for planning seismic acquisition onshore and in shallow water.

LINEAMENT AND GEOMORPHIC ANALYSIS OF REMOTE SENSING DATA AS AN AID
TO HYDROCARBON EXPLORATION, SIRT BASIN, LIBYA

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SUMMARY

The Sirt basin, in semi-arid north-central Libya, provides an ideal case study to evaluate different remote sensing data sources for hydrocarbon exploration.

Remote sensing images, including Landsat-TM, SIR-A and aerial photos, were compared with subsurface maps constructed from data of approximately 200 wells, using a geo-information system (GIS). An additional gravity map and some stratigraphic and structural cross-sections were also included in the comparison, covering the area of the Landsat-TM frame (WRS 185/040).

The Precambrian basement in the basin is overlain by an approximately 5000 to 5500 m thick sedimentary sequence of mainly Upper Cretaceous to Miocene age. The hydrocarbon source rock is dominantly Upper Cretaceous in age. Oil reservoirs are located in horsts and associated traps of a NW trending horst and graben system that is related to the post-Early Cretaceous subsidence of the basin.

Oil production is currently from five different stratigraphic horizons of Paleocene and Eocene age. The production horizons are shallow at the western basin margin, gradually increasing in depth towards the center of the basin. This disposition is advantageous to study the surface expression of progressively deeper buried oil reservoirs, and one of the objectives in this regard is to relate surface features to depth of potential reservoirs. This will attribute to a quick appraisal of future prospective areas, using remote sensing data.

A lineament analysis was made using the Landsat-TM and SIR-A images to study the surface expression of basement faults and their relationship to known oil fields. The results indicate: (1) that a strong relationship exists between basement faults and surface lineaments, despite an approximately 1000 m thick evaporite-bearing formation, (2) that eight of a total of twenty-two oil fields in the area are located in areas of intersection of lineaments, in all cases near major lineament trends.

Detailed geomorphic interpretation of Landsat-TM and aerial photos indicated that another six of the oil fields coincide with geomorphic anomalies (other than lineaments).

The results of this study suggest that specific prospective areas can be delineated. Therefore, a cost-effective exploration programme should benefit from remote sensing data analysis.

MAPPING THERMAL MATURITY VARIATIONS IN THE CHAINMAN SHALE NEAR
EUREKA, NEVADA, USING LANDSAT THEMATIC MAPPER IMAGES

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SUMMARY

Recent laboratory studies have shown that rocks containing organic matter (OM) exhibit systematic visible and near-infrared (VNIR) spectral reflectance variations related to the OM thermal maturity. The spectral variations generally include decreasing reflectance and absorption band intensities associated with increasing levels of OM thermal maturation. VNIR reflectance variations are most prominent between 0.90 and 1.50 μm and are highly correlated with the contained OM vitrinite reflectance and hydrogen/carbon values.

To evaluate the usefulness of remote VNIR spectral reflectance measurements for mapping thermal maturity variations, well exposed, sparsely vegetated areas underlain by the Chainman Shale were studied in a Landsat TM image centered near Eureka, Nevada. The relation between VNIR spectral reflectance and thermal maturity was established in the laboratory by comparing reflectance to vitrinite reflectance (R_m) for samples collected from 20 sites distributed along the north-trending exposures of Chainman Shale.

Convolving laboratory spectra with the TM bandpasses showed that mean TM4/TM5 values for fresh rock surfaces increase as R_m increases. The rate with which the TM4/TM5 values change appears to decrease near the mature-superature transition ($R_m \approx 2.0$ percent). Spectra of weathered rock surfaces yield larger TM4/TM5 variance, but the trend and distinction between mature and superature samples are still evident.

A TM4/TM5 image-map was prepared at a 1:62,500 scale by applying a TM4/TM3 digital number mask to eliminate pixels containing vegetation and, then, subdividing the digital number range into four categories. The boundaries of the four categories were based on the locations of groups of data plots observed in the laboratory plot of R_m and TM4/TM5. We estimate that the TM4/TM3 mask eliminated all pixels having vegetation cover > 10 percent. In the image-map, which was prepared without atmospheric corrections or radiometric calibration, all the pixels having high TM4/TM5 values are located within excellent Chainman Shale exposures in the Diamond Mountains; in contrast, only low to moderate TM4/TM5 values are present within exposures to the south. These results are consistent with published thermal maturation estimates based on Rock-Eval pyrolysis data and conodont alteration indices.

We conclude that remote spectral reflectance measurements can be used to map thermal maturation differences within selected stratigraphic horizons. The main limitation for practical application in vegetated areas is the lack of an adequate method for determining the spectral reflectance contribution of various plants; several approaches are being evaluated. Other important factors appear to be the composition and abundance of OM and the lithologic composition.

CORRELATION OF IMAGING SPECTROMETER AND GROUND DATA
FOR ALTERATION MAPPING AT YERINGTON, NEVADA

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SUMMARY

The Mesozoic Yerington Batholith in west central Nevada has a well developed hydrothermal alteration zone. Miocene extensional basin-and-range faulting rotated the deposit nearly 90°, resulting in a horizontal exposure of the originally vertical hydrothermal system. Parts of the system have been mapped in great detail. The excellent horizontal exposures of batholith-scale alteration zoning and previous mapping make this an ideal test area from imaging spectrometry. Data from a 63-channel imaging spectrometer were acquired over the axis of the hydrothermally altered zone. Several hundred 288-channel ground spectra were also acquired in various parts of the alteration zones. Processed spectra from the two datasets are well correlated, and can be used to produce an alteration map which matches previous, detailed alteration maps.

TM PROCESSING FOR ROUTINE USE IN MINERAL EXPLORATION

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SUMMARY

Thematic Mapper data is now routinely used in mineral exploration. This use places demands on the style and presentation of image type data not readily appreciated by the expert user community. Our group has strived to clearly present in an unbiased manner the new information existing in TM data to the geologist in the field. This paper discusses the technical criteria we have applied during our processing to achieve consistency and quality in a product which goes out to be used in the field by a geologist who may be relatively unfamiliar with the manner in which it was produced.

Prior to being released all images are geocoded to a standard map frame. This is usually a UTM 1:100000 or 1:50000 USGS quadrant or NTS basemap.

For regional structural interpretation, TM images are used like photographs. This is straightforward and only requires high quality contrast balanced images with appropriate bands. These images are also of great value for geological mapping, and as reference images to locate oneself on the ground.

To use the spectral information in TM images to map altered areas requires a great deal of care in processing the digital data. Obvious features stand out clearly even with sloppy processing. However, false anomalies are easily introduced, and can result in considerable expense when followed up in the field. Our processing stream includes a path radiance correction, classification, a calculated correction for vegetation effects, and masking of pixels without geologic information. The final product is a parameter called a clay index which characterizes the geological contribution to absorption in the TM band 7 and an iron index which is related to iron oxide absorption effects in the ratio of TM3/TM1. Our final product is a paper map suitable for copying or dylene printing. In addition, subsets of archive image files can be viewed on simple image display systems running on standard personal computers in the field.

RELATING GROUND MINERALOGY VIA SPECTRAL SIGNATURES TO 18-CHANNEL
AIRBORNE IMAGERY OBTAINED WITH THE GEOSCAN MKII ADVANCED SCANNER:
A 1989 CASE HISTORY FROM THE LEONORA, WESTERN AUSTRALIA GOLD DISTRICT

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SUMMARY

The advanced Airborne Multi-Spectral Scanner (AMSS-MKII) is a new 46-channel imaging spectrometer built in 1988 for commercial use in mineral exploration by Geoscan Pty. Ltd., a gold-mining and - exploration company based in Western Australia. The scanner has 3-axis stabilization, can be calibrated and has grating-dispersive optics and 3 sets of linear-array detectors, operating in the visible and near-infrared (VIS-NIR), shortwave-infrared (SWIR-8 channels) and in the thermal bands (TIR-6 channels -- due for installation in April 1989). Due to the very high data-acquisition rate (0.4 Mbytes/sec) the data are recorded onto optical discs (WORM) in flight. However, only 24 bands of the 768-pixel-wide imagery can be recorded. Band selection decisions in the VIS-NIR bands may be made while in flight, and are tailored to the target type being studied -- for vegetative targets 36 VIS-NIR bands are available, while for mineral exploration the emphasis is placed on the SWIR and TIR bands. Real-time color display in the aircraft is available for any algorithm. The nadir-pixel in each scan line is georeferenced to UTM or to latitude-longitude coordinates, and the system is GPS-ready.

The optical disc recordings can be immediately analyzed on the ground, using proprietary (portable) image-analysis (GIPSy) units which accept the raw-data optical discs directly. Automatic correction for atmospheric-backscatter, and for panoramic-scanning are available, for real-time modification of the imagery during read-in.

The system is to be operated in North America mineral exploration in 1989.

The problem being addressed at Leonora, W.A. is to search for new gold-bearing mineralization in Archean mafic-ultramafic rocks which have been deeply-weathered (30-50 m) with concomitant formation of ferricrete (ferruginous aluminosilcretes) and/or true lateritization. Unlike much of the Western USA (where remote sensing "evolved"), with its relatively-recent rocks and very thin weathering rind, the present day surface minerals in the Western Australia goldfields often bear little resemblance to those formed during the original hydrothermal mineralization. One is therefore forced to understand both the post-Permian weathering cycle, with its strong leaching and formation of its own characteristic minerals, as well as to identify

those more-resistant "survivors" of the original mineral suites, and to design the spectral search accordingly.

The methodology used is to fly the scanner, initially at a low altitude with 3-meter pixels to develop characteristic spectral signatures for the terrain. A flight then at higher altitude is used to obtain the operational-type regional coverage (typically at 8-10 meter pixel sizes). Over 400 spectral measurements have been taken with a GER IRIS spectrometer, from samples collected at locations which were shown to be "anomalous" with the scanner, and used to relate the present-day surface mineralogies with those digital image-signatures extracted from the scanner imagery.

The paper will show how the first result from the SWIR spectral signatures obtained from the ground data (means and standard deviations) is the application to stratigraphic differentiation between Al- and Mg-rich clays and micas in the imagery, followed then by refinements within these two mineral groupings. The high signal-to-noise ratio (SNR) of the new imaging system (50:1 to 100:1 in flight imagery, within the SWIR bands) allows band-difference images rather than band-ratio images to be used, with the retention of the good SNR. This feature alone offers material advances over any imaging spectrometer flying today.

COMPARISON OF LANDSAT THEMATIC MAPPER IMAGES AND
GEOPHYSICAL AND ENVIRONMENTAL RESEARCH
IMAGING SPECTROMETER DATA FOR ALTERATION MAPPING

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SUMMARY

LANDSAT Thematic Mapper (TM) images and Geophysical and Environmental Research Imaging Spectrometer (GERIS) data were analyzed for the Cuprite mining district, Esmeralda and Nye Counties, Nevada, and compared to available geologic and alteration maps of the area. Both data sets were calibrated to reflectance for comparison with measured reflectance spectra. Color composite and color-ratio-composite TM images were used to map the general distribution of alteration. Individual and spatially averaged spectra were extracted from the GERIS images, compared to the laboratory spectra to identify minerals, and used to classify the images in the spectral domain.

The TM data with 30 meter resolution and 6 broad bands allowed discrimination of general mineral groups. The clay minerals, silica, playa deposits, and unaltered rocks were mapped as discrete spectral units, but specific mineral types were not determined. In contrast, the GERIS utilized many narrow contiguous spectral bands to construct detailed reflectance spectra while retaining the image format. The 15 meter spatial resolution and 63 spectral bands permitted identification of specific minerals. The GERIS images and detailed spectra extracted from the images provided the ability to identify the mineral alunite and kaolinite in the Cuprite district by their spectral characteristics. Alunite was identified by the presence of a broad 2.16 μm absorption band and weaker bands at 2.32 and 2.42 μm . Kaolinite was identified by the presence of a doublet feature at 2.16 and 2.20 μm . Because of the GERIS spectral resolution (about 17 nm in the 2.2 μm region), the 2.16-2.20 μm kaolinite doublet usually appeared as an asymmetrical 2.18 μm band.

The TM images discriminate a circular alteration pattern at Cuprite but do not allow identification of the specific alteration minerals. The GERIS data show a concentrically zoned hydrothermal system. A central silica cap mapped previously using conventional field mapping was not distinguishable using the GERIS because silica does not have distinct absorption features in the 0.4 to 2.5 μm region. The imaging spectrometer data show that the first zone out from the silica cap consists primarily of alunite. A kaolinitic zone is found farther from the center. Areas of ammonium enrichment near the northwest edge of the former hydrothermal system were also identified by using the GERIS data to detect the presence of the mineral buddingtonite. Buddingtonite is an ammonium bearing feldspar discovered in the Cuprite district using the NASA Airborne Imaging Spectrometer (AIS). Buddingtonite is difficult to recognize in the field but is found using imaging spectrometer data by the presence of a broad 2.11 μm

absorption band and a secondary narrow band near 2.01 μm . Identification and mapping of the ammonium feldspar using the GERIS system is especially significant for precious metals exploration because this mineral is often associated with hot springs type gold deposits.

GEOLOGIC MAPPING AND MINERAL EXPLORATION IN THE
COPPIN GAP GREENSTONE BELT, AUSTRALIA

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SUMMARY

Coppin Gap in the Marble Bar District of Western Australia lies in an Archaean greenstone belt within the Pilbara craton. Exposed is a sequence of mafic and ultramafic rocks, including mafic volcanics, metamorphosed high-magnesia basalts, peridotite, serpentinite, pyroxenite, and carbonate-talc rocks. Economic interest in the area centers on gold-bearing quartz-vein deposits and porphyry copper/molybdenum occurrences. Exposures are excellent, and vegetation cover and development of a deep weathering layer are modest.

AIS, TIMS, and N-001 airborne multispectral scanner data were acquired simultaneously over the area in 1985, and TM data were obtained in 1987. These data were computer processed and analyzed to achieve the following objectives: 1) to identify variations in mineralogy of the different rock types as a function of their spectral reflectance and emittance characteristics; 2) to assess the capabilities of the individual instruments and to contrast geologic information available from the different wavelength regions sensed by the scanners; 3) to map the spatial distribution and variation of rock types and mineralogical changes in the Coppin Gap area; 4) to assess the utility of these data for mineral exploration.

Results of the study are: 1) variations of mafic and ultramafic rock types can be mapped using a combination of scanner data; 2) thermal emittance data complements information available in the visible and near infrared; 3) imaging spectrometer data could be used to identify mineralogical components, as opposed to simple separation achievable with broad-band instruments; 4) alteration associated with the porphyry deposits was identifiable; 5) quartz veins could be mapped using thermal data.

This work was performed at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration.

REMOTE SENSING AND MINERAL EXPLORATION IN ARCTIC TUNDRA:
A CASE STUDY IN THE NORTHWEST TERRITORIES, CANADA

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SUMMARY

This paper discusses the integration and study of a multiple data set constructed for the Bathurst Inlet area, District of MacKenzie, in the Northwest Territories of Canada. Environment Canada and the Geological Survey of Canada have studied the area to assess its potential for a national park site and for mineral exploration, respectively. Part of the area between Turner Lake and Pistol Lake is of sufficient interest that, in the summer of 1989, it will be mapped at scale 1:10,000 by a team of university, industry, and government geologists. Until recently, no particular use was made of remotely sensed imagery, however, the authors felt that the typical climatic and physiographic characteristics of the area are such that remote sensing successfully portray important geological information.

The data integration methodology to produce sets of co-registered digital images at different resolutions is discussed and generalized in terms of the requirements of geographic information systems for remote sensing analysis using both mini- and micro-computer technology. Preprocessing and data analysis are described to derive viable strategies for arctic glaciated terrains which include coastal areas of the inlet.

The results of image enhancement and classification to aid in geological mapping and exploration are discussed to assess the following points:

- (a) usefulness of seasonal LANDSAT MSS, SEASAT, and SPOT imagery;
- (b) contribution of airborne SAR imaging to geological mapping;
- (c) type of multidisciplinary knowledge required for image analysis and interpretation;
- (d) relevance of easily available geophysical, geological, and topographic data integrated with remotely sensed images;
- (e) the feasibility of using archival imagery to systematically map coastal areas in the Arctic regions of Canada;

- (f) similarity of the study area with other large areas of mineralized terrains in North America, northern Europe, and northern U.S.S.R.

MAPPING HYDROTHERMAL ALTERATION IN THE GOLDFIELD MINING DISTRICT,
NEVADA, WITH THE AIRBORNE VISIBLE AND INFRARED IMAGING SPECTROMETER (AVIRIS)

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SUMMARY

The Airborne Visible and InfraRed Imaging Spectrometer (AVIRIS) is 224-channel scanner built by the Jet Propulsion Laboratory, and operated by NASA's Ames Research Center. AVIRIS acquires simultaneously 224 channels of data in the 0.4 to 2.5 micron region of the spectrum, with an average spectral resolution of 10 nanometers. Operating from NASA's ER-2 at an altitude of 20 km, the IFOV is 20 m with a swath width of 10 km. This is the first instrument of its kind to obtain complete high spectral resolution reflectance data with a wide swath width.

Data were acquired over the Goldfield Mining District, western Nevada, in September 1987, August 1988, and April 1989. The Goldfield area was the site of extensive gold and silver mining activities earlier in the century, and currently supports minor activity. Goldfield is one of a group of large epithermal precious metal deposits in Tertiary volcanic rocks, associated with silicic volcanism and caldera formation. Hydrothermal alteration and metal deposition occurred 20 My ago; alteration consists of silicification along fractures, advanced argillic and argillic zones further away from veins, and more wide-spread propylitic zones. Alteration minerals include alunite, kaolinite, illite, adularia and opal, montmorillonite and chlorite.

AVIRIS data were pre-processed to correct them for line-by-line dark current variations and detector read-out delays. Since no portable field spectrometer was available at the time of the overflight, retrieval of ground reflectance was done using the flat-field correction technique. This correction procedure does not require radiometrically calibrated data and compensate for the atmosphere. The only inconvenience of this method is that it does not compensate for path radiance, which can be a problem in the visible part of the spectrum, resulting in shift in wavelength for some features.

Analysis of the data was performed to extract spectral information, mainly concentrating on the 2 - 2.45 micron window, as the alteration minerals of interest have their distinctive spectral reflectance features in this region. Occurrence of the various minerals were located in the image data, and identified by spectral matching with library curves. Maps were made of the spatial occurrence of the individual minerals over the entire scene; finally mineral mixture maps were produced in an attempt to show the relative abundance of various minerals on a pixel-by-pixel basis.

Field work was done to verify the image derived mineral maps; representative samples of the outcrops were collected; lab PIDAS (Portable Instant Display and Analysis Spectrometer) and Beckman UV5240 spectra of the samples were acquired and compared to the ones obtained from

AVIRIS; XRD analysis of the samples was performed. In all cases, the various analysis verified the results of the AVIRIS products.

This test demonstrates the unique capabilities of high resolution imaging spectrometers for alteration mapping and identification of mineralogy. This is a major breakthrough in remote sensing by allowing us to go beyond drawing boundaries around unidentifiable color regions on images, and to produce accurate mineral maps.

LITHOLOGICAL INFORMATION IN ENHANCED LANDSAT
THEMATIC MAPPER IMAGES OF ARID REGIONS

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SUMMARY

Well exposed arid and semi-arid terrain provide excellent testing grounds to investigate the amount of lithological information that can be extracted from enhanced Landsat Thematic Mapper (TM) data. This study will discuss how criteria may be developed to allow for direct interpretation of the enhanced data by the integration of the image data with geological maps and information from fieldwork of a geologically understood part of a scene. These criteria may then be applied to poorly understood and less accessible parts of the same scene allowing for direct lithological interpretation. The use of ratios to enhance hydroxyl-, carbonate-, and iron-rich lithologies provide additional information as to the sensitivity of the TM data to variations in these components. Convolution of laboratory spectra of samples from the region in question to the TM bandpasses, and the correction of both these spectra and TM data of equivalent lithological units to radiance show that the variations evident on the image are due to real lithological factors. It is discussed how the combination of the enhanced images, ratio images and extracted radiance spectra may be applied to geological exploration of a poorly known arid region. The aim of this study is to show that the broad band TM data are a powerful tool for geological mapping and exploration even in the absence of so called 'ground truth'.

APPLICATION OF GEOSCAN AMSS MKI DATA TO LITHOLOGIC MAPPING
IN QUEENSLAND, AUSTRALIA

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SUMMARY

Lithologic mapping has been done using image data obtained by Geoscan's Airborne Multispectral Scanner (AMSS) Mk I, which has thirteen spectral bands: five in the visible and near-infrared (VNIR), four in the short-wavelength-infrared (SWIR), and four in the thermal infrared (TIR) region respectively. Only the VNIR and SWIR bands were used in this study. The test area is located near Ravenswood in Queensland, Australia, and occupied mainly by Ravenswood Granodiorite Complex of Middle Ordovician, and Upper Silurian or Lower Devonian age.

Two calibration techniques were applied to the data in order to convert digital numbers (DN) to ground reflectance. One is the linear regression method using field reflectance measurements, but the result was not reasonable judging from the calibrated inter-band patterns, probably due to inhomogeneity of the ground calibration targets with sparse vegetation cover of eucalyptus trees. The other technique employed was the Log Residual, which normalizes a DN value of each band of each pixel using geometric means over each band and each pixel, and is considered to remove topographic and illumination effects. In this case, the Log Residual among the three SWIR bands provided a reasonable result which presumably corresponded to a reflectance pattern of each pixel.

The Alunite Index and the Calcite Index were calculated by linearly combining the "calibrated" values of the three SWIR bands. The Perpendicular Vegetation Index was also obtained from the two VNIR bands. Then, a color composite image was created by assigning these three spectral indices to color primitives.

Another technique tested was the HSI color transform. The (1:1:1) line in the "calibrated" values of the three SWIR bands was chosen as the I (intensity) axis. The I and S (saturation) values were fixed to 0.5 and 1.0 respectively in order to achieve maximum enhancement of H(hue) values.

Both techniques successfully created color images which were easy to interpret geologically. The colors displayed on the images corresponded to specific inter-band patterns representing typical rock or mineral types. For instance, epidote-rich zones and sericite-rich zones in granodiorite were clearly delineated on the processed image.

THE AUSTRALIAN LANDSAT TM STORY: A COMMERCIAL SUCCESS

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SUMMARY

The Australian Mineral Industry Research Association Limited (AMIRA) manages industrial multi-client R&D for the resource industry. In 1984, it formed a consortium to modify the Australian Landsat receiving facility to enable Thematic Mapper (TM) data reception in an experimental mode. This paper provides an account of this most successful AMIRA project called the Signal Processing Experiment and the marketing strategies that enabled TM digital data sales by AMIRA at an annual rate of \$1m, of which 90% was to industry.

The Signal Processing Experiment involved hardware modifications to the Landsat MSS reception facility which were undertaken by CSIRO and operated by Australian Centre for Remote Sensing (ACRES) under their continuing agreement with NOAA. Because of the industry interest in obtaining TM data over Australia, AMIRA and CSIRO raised financial support from mineral explorers and government research bodies.

AMIRA coordinated the selection of TM scenes for evaluation by the 33 member organisations of the consortium while Resource Industry Associates (RIA) arranged the archiving, copying, and distribution of the 16 TM CCTS to each member. Many consortium members experienced difficulties in coping with the data handling requirements of the large TM data sets. Due to the success of the experimental facility, the ability of AMIRA and RIA to operate a very low cost distribution operation, and the lack of full upgrade to ACRES facilities, AMIRA was awarded distribution rights for TM.

The paper outlines the strategies for very successful marketing of remote sensing digital data to new and existing users. Such strategies were based on several key features of how remote sensing has developed in Australia.

- AMIRA has been a link between research groups and mineral explorers for 30 years. During the past 10 years, \$2.5 m has been committed through AMIRA and its petroleum division APIRA by mineral and petroleum explorers to a range of modest research projects conducted by CSIRO. From this has developed a close interaction between industry and researchers in remote sensing. We had in effect prepared a part of the marketplace for the arrival of TM through our Aircraft Thematic Mapper studies relating to gold exploration.

AMIRA is owned by 100 mining and oil companies so was in an ideal position to gauge the impact of TM production. Considerable experience was gained particularly with overcoming the negative effect created by the lack of success of Landsat MSS for mineral exploration. However, the gold exploration boom in Australia provided significant opportunities for explorers to try new technology such as TM.

AMIRA recognised that to expand the usage of TM data in the exploration industry, several initiatives were needed:

- multi-client projects to evaluate TM;
- workshop courses;
- development of optical disk and subsequently opto-magnetic data storage sub-systems for portable computers; and,
- development of a sophisticated user friendly image processing software package that is operated on many types of computers by field geologists.

The introduction of this technology has at times been frustrating but most exciting.

AN AIRBORNE RADAR PROGRAMME FOR GEOLOGISTS

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SUMMARY

Since 1987, the Canada Centre for Remote Sensing (CCRS) has provided airborne synthetic aperture radar (SAR) data to more than 50 geologists located in all parts of Canada. The data were acquired as part of a programme designed to encourage geologists to become more familiar with airborne radar and to encourage them to explore new radar applications. Through this programme, radar images are being used to map lithologies and structures from Precambrian to Recent in age, and to support research in exploring for hydrocarbons, base and precious metals, and industrial minerals. Ongoing technical studies are concerned with the production of mosaics, working with stereo models, developing a variety of radar enhancement techniques, and examining ways to integrate radar with other datasets.

The radar data are collected using the CCRS's Convair 580 aircraft and SAR system which transmits in C and X frequencies and images the ground in three modes: Nadir (0-72° incidence, 19 km wide swath), Narrow (45°-76° incidence, 18 km wide swath), and Wide (45°-85° incidence, 63 km wide swath). The data are recorded digitally. Index maps of the 34 test sites can be requested from the CCRS. Copies of the images can be ordered from the National Air Photo Library in Ottawa. CCTs of specific scenes can be purchased from the CCRS.

This programme is organised by the Non-Renewable Resources Group, Applications Division of CCRS, and is funded by the Radar Data Development Programme.

MOMS2-02 A NEW PERSPECTIVE IN EARTH OBSERVATION REMOTE SENSING

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SUMMARY

The availability of spectral and spatial high resolution remote sensing data is a basic requirement of most of the earth oriented user community. In addition, stereoscopic data acquisition was requested, especially by those users engaged in topographic mapping, areal surveys in general, and planning activities.

The French SPOT system was the first which took into account this need. Although the success of this system is obvious, the data made available suffers under distinct disadvantages, which have been documented by different publications.

On the basis of the great success of the MOMS-01 camera (MOMS = Modular Optoelectronic Multispectral Scanner), which was the first CCD-system flown in space in 1983/84, the German Minister for Science and Technology decided to develop the significantly improved MOMS-2 which is scheduled for a space shuttle flight in the framework of the German D-2 Mission in 1992.

The most striking elements of this camera can be summarized as follows:

- Four multispectral bands in the visible and near infrared range of the electromagnetic spectrum: on the basis of extensive preinvestigations, the following narrow bands have been selected:
 - band 1: 440 - 505 nm,
 - band 2: 530 - 575 nm,
 - band 3: 645 - 680 nm,
 - band 4: 770 - 810 nm;
- high resolution panchromatic band (520 - 760 nm); it is planned, to realize a ground resolution of 5 m;
- in-track stereoscopic data acquisition by additional 2 tilted optics looking forward and backward.

On the basis of these data, significant improvements for wide ranges of fields of applications can be expected. Especially the simultaneous acquisition of stereoscopic and multispectral data promises far reaching influences over a better detection and association of a broad variety of surface features.

ACCESS TO REMOTE SENSING DATA FOR GLOBAL RESOURCE EXPLORATION

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SUMMARY

Landsat and SPOT have demonstrated the usefulness of satellite remote sensing for worldwide energy and mineral exploration through lowering cost and improving exploration risk. While revolutionary for regional exploration mapping, the satellites have employed sensor systems of relatively low spectral and spatial sensitivity. During the 1990's, experimental systems, such as NASA's Earth Observation System, (E.O.S.), and research/operational satellite systems now under development in the U.S., Japan, Soviet Union, France, BSA, Canada, India, China, and others will provide sensors of much greater sensitivity for enhanced mineralogical, lithological, and geobotanical identification. Coupled with improved geographic information systems and data integration techniques, these more sensitive satellite data will significantly improve exploration mapping and geologic modeling for energy and mineral resources worldwide.

While the past 17 years of civilian satellite remote sensing programs have operated under the principles of "open skies" and "non-discriminatory access to data," the growing cooperation of more sensitive data from government research/operational, and quasi commercial systems will occur with presently no clear indication whether these data will be disseminated on a timely non-discriminatory basis for nonresearch "commercial uses." The key issue effecting the use of this data in the 1990's will be their availability and timeliness of access from international government research programs, government data distribution agencies, and commercial data suppliers and service/information industries. If future government policies allow for restrictions for these more sensitive data, then international satellite remote sensing could come under national or proprietary constraints and become unavailable to the global energy and mineral exploration community at large.

GAS-SENSING RADAR SURVEY INTERPRETATION

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SUMMARY

Interpretation of gas (propane)-sensing radar survey patterns has advanced dramatically in the past three year. This survey method is unique. It is the only remote sensing method that "sees" live gas seepage in two dimensions. Observed and mapped gas seepage patterns from surveys performed in the United States, the Mideast, and Africa have been modeled. Although the gas seepage patterns can be strongly affected by local geologic conditions, fracture control is the dominant feature of most patterns.

Basically, fracture-controlled gas seepage forms linear and rectilinear surface patterns that correlate very well with fracture sets that can be delineated on aerial photographs, satellite imagery, side-looking radar imagery, and topographic maps. Curved and curvilinear gas seepage patterns often correlate with gas seepage that is laterally deflected by near-surface, gas seepage-induced, diagenetic carbonate and sulfide cementation above hydrocarbon reservoirs. The linear and curved patterns commonly blend together, particularly where there are stacked hydrocarbon reservoirs. The net effect is that gas seepage patterns observed on radar are controlled by surface and near-surface fractures and the surface pattern may be quite different from the shape of the reservoir(s) below.

Gas seepage pattern models developed to date include sand channels, faults, domes, tilted fault blocks, stratigraphic pinchouts, and pinnacle reefs. Variations of a model, or mixed models are more common in the field than pure models.

AN IMPROVED APPARENT THERMAL INERTIA MODEL

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SUMMARY

The use of thermal inertia remote sensing techniques enable us to obtain more information below the ground surface. In geological and hydrological applications, the thermal inertia is a useful tool. The apparent thermal inertia can be calculated from the diurnal variations of the surface temperature and albedo. However, there exists strong influences of various interfering factors such as the sensible and latent heat fluxes. It is important to remove to influences.

A new apparent thermal inertia model was derived from the heat balance equation of the surface and soil heat flux equation. With this model, the influence of the sensible heat flux can be removed by using remote sensing information only. The results of field experiments made in recent several years indicate that the calculated accuracy of the apparent thermal inertia is improved using the present model.

THE SEISMICAL TECTONIC BACKGROUND REVEALED IN THE
SATELLITE THERMO-INFRARED IMAGERY OF WEST YUNNAN

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SUMMARY

This paper introduces the application of satellite thermal infrared imagery to seismological investigation first time in China. In these thermo-infrared images of West Yunnan, about 20 linear thermal anomalies are interpreted. Analysis of the anomalies together with geophysical data and investigation in situ was made. The result indicates that these lineaments correspond well with deep faults. Based on structural geomorphology interpretation of these and other remotely sensed images, some new data and view points are presented as follow:

1. The thermal lineaments in the area to west of the Mountain Cangshan form in a network and show a lot of uniform and dense fractures existing in the area. It would demonstrate that the stress field and/or the medium of this area are uniform to a certain degree so that the interior energy releases easy. It may be the reason why the seismicity in the area is so low.
2. The Yanyuan-Lijiang active block affirmed recently is apparent in the multi-band image. In the center of the block, the Chenhai-Binchuan Fault runs a curve and it agrees well with the sharp bends of crust thickness contours, that indicates a plutonic tectonic and would be the cause of the earthquake of 7.5 at Yongshen in 1511 and several quakes by Ninglang.
3. The Chuan-Dian faulting block, moving southeastward, is obstructed by the southwestern block of Honghe Fault. The interaction of both the blocks causes (Author calls it "tear up") some NW faults and several earthquakes at the southern ends of three large SN faults. The magnitude of these quakes depends upon the magnitude of load, i.e., the dimension of blocks surrounded by the Honghe Fault with above mentioned NS faults respectively.

SPECTRAL BAND SHAPES AS CRITERIA FOR MINERAL
DISCRIMINATION IN FIELD SPECTROSCOPY

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SUMMARY

In the 25 years since the famous Hunt & Salisbury papers on mineral spectra were published, most workers have used those spectra to extract the specific wavelength **positions** for recognizing the minerals in their own spectral measurements. Almost without exception, the **shape** of the spectral peak was not utilized, but recently the use of "feature extraction" algorithms enabled the smaller shoulders on composite peaks to be extracted from the curves. Such algorithms require additional computer time, often doubling at least the time required for pattern recognition. With the growing interest in placing "expert" systems of software in micro-code into the spectrometers themselves, any reduction in the codes in size and or/in speed of calculation is to be appreciated.

The methodology described in this paper is to encode **both the minimum wavelength position and its symmetry** (or shape) into the short 12-character-string which results from our STANXPRT system of pattern recognition (Goetting & Lyon, IGARSS-86). A simple calculation is made of the widths for both the shorter- and the longer-wavelength sides on either side of the peak minimum. This then followed by a greater-than or less-than decision to assess if the shape is left-asymmetric (a), symmetric (s), or right-asymmetric (b).

The kaolin group minerals are nearly always left-asymmetric (a), with the exception of dickite, where the 1400 and 2200 nm doublets are resolvable into four symmetric minima. The montmorillonite group minerals are always right-asymmetric (b) at 1400 and 1900 nm, but are usually symmetric(s) at 2200 nm. Sericitic micas (al-rich) are usually symmetric(s) in all three positions -- 1400, 1900, and 2200 nm.

The attached figure helps to explain the symmetry-asymmetry concept. The inclusion of this simple extra measure into the coded-string allows very much simpler logic codes to be written into the expert system software. This is another example of the beneficial results from more effort by the original "expert" in explaining their decision-making steps leading to decreased complexity of the subsequent programming.

MEASUREMENTS OF THERMAL INFRARED REFLECTANCE SPECTRA
OF ROCKS AND MINERALS

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SUMMARY

It is well known that silicate minerals exhibit characteristic spectral features in the atmospheric window in the thermal infrared region (8 to 14 μm). Therefore, it has been recognized that multispectral data in this region would be useful for lithologic discrimination. Thermal emission or reflection spectra of rocks and minerals are fundamentally important for considering remote sensing techniques in the thermal infrared. However, such data are not sufficient for more quantitative discussions at the moment.

The authors have started measuring thermal infrared reflectance spectra of various rock and minerals in order to provide basic data for multispectral thermal infrared remote sensing. The equipment consists of a FTIR (fourier transform infrared spectrometer), an attachment for diffuse reflectance measurements, and a personal computer for data processing. Reflectance spectra of typical silicate minerals and "Igneous Rock Series" of the GSJ (Geological Survey of Japan) rock reference samples will be shown in this paper.

For an effective use of the spectral data, a thermal infrared spectral database is also being constructed. It covers not only the spectra of rocks and minerals measured by the authors but also those digitized from published data. The concept of the database and an example of output will be shown in this paper. Experimental rock type discrimination and other analytical methods using the database will be shown.

MULTILEVEL IMAGE ANALYSIS OF PRECAMBRIAN ROCKS,
WESTERN OWL CREEK MOUNTAINS, WYOMING

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SUMMARY

The western Owl Creek Mountains, Wyoming comprise an en echelon series of northwest-trending folds bounded by reverse faults. The Sheep Ridge and Harris Ridge anticlines are two similar folds in this area that are eroded to different structural levels. Precambrian rocks crop out in the core of the Sheep Ridge anticline and the basement-sediment contact is well-exposed on both flanks of the fold. The Precambrian core of the Sheep Ridge anticlines is a granite gneiss complex which varies in composition from granitic to tonalitic gneiss. The heterogeneous complex also includes mafic and felsic dikes, ultramafic pods, and garnet-cordierite paragneiss. Lithologic and trend data were derived from field mapping and measurements of foliation planes, fractures, faults, dikes, and shear zones. Landsat Thematic Mapper (TM) images were enlarged to a 1:24,000-scale and digitally processed by principle-components transformation to enhance lithologic contrasts within the Precambrian basement. In addition to Landsat multispectral images, high-altitude color-infrared (CIR) aerial photographs were used for mapping because of their excellent spatial resolution.

Multilevel sensing is a useful tool for structural analysis because regional reconnaissance mapping can be done quickly from small-scale space imagery, and local features of interest can be viewed in detail from larger scale imagery. In addition to improved resolution, CIR photography provides the opportunity to map structural features at different sun azimuths. Photolinear trends determined from multilevel sensing show a dominant 0-10E and N20-60E orientation. The 0-10E trend shows a positive correlation with the fracture data obtained from field measurements. The fractures appear to form basement zones that are detectable on very small-scale space imagery. The fracture zones form conjugate sets in the Precambrian basement which may control the development of Laramide structural patterns. Photolinear features trending northeast may be indicative of the orientation of fracture and shear zones in the Precambrian basement. Northeast-trending basement zones in the southwest flank of the Sheep Ridge anticline correlate with deeply eroded drainages. Outcrops in the drainages show evidence of cataclastic deformation and the presence of secondary minerals epidote and chlorite. Late Precambrian basement zones are thought to contain retrograde mineral assemblages of chlorite-actinolite-epidote which are easily eroded and form recognizable basement structural trends on Landsat imagery.

RELATIVE ABSORPTION BAND-DEPTH IMAGES: USE IN IMAGING
SPECTROMETER DATA ANALYSIS AND CALIBRATION

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SUMMARY

Relative absorption band-depth (RBD) images provide a straightforward technique for analyzing imaging spectrometer data without the use of arbitrary normalization procedures. To construct an RBD image, data channels are selected that correspond to the high and low wavelength shoulders of a mineral absorption feature. The digital number (DN) values of these shoulder channels are summed and then divided by the DN values of a channel positioned at the absorption minimum. RBD images are highly sensitive to the absorption features that they are designed to detect. The images also are simple to interpret based on a knowledge of mineral spectral reflectance properties.

Previous work using RBD images has focused on selected band combinations believed to be of special mineralogical significance. The current study takes a more general approach whereby all possible RBD images are formed and then analyzed for their information content. This approach reduces the chance that important, but unanticipated, mineral absorption features will be overlooked in a study area.

For this study, we examined airborne imaging spectrometer data acquired by Geophysical Environmental Research (GER), Inc., over the Cuprite mining district in west-central Nevada. The study area contains good exposures of hydrothermally-altered rocks, composed mainly of the minerals alunite, kaolinite, chalcedonic quartz, and buddingtonite (an HN_4 -rich feldspar). Although the GER scanner provides data throughout the visible and near-infrared (0.4-2.5 μm) wavelength range, we focused on 26 data channels positioned between 2.03 and 2.44 μm -- a wavelength region where many minerals exhibit diagnostic molecular vibration absorption bands.

The number of RBD images that can be constructed from an imaging spectrometer data set is given by:

$$\sum_{s=2}^n n-s$$

where "n" is the number of input channels, and "s" is the number of channels separating the shoulder channels used in each RBD image. In practice, not all the possible RBD images need to be examined, because the bandwidths of many images will be either too narrow or too broad for discerning mineral absorption features. From the 26 GER input data channels, 76 RBD images

were generated with bandwidths ranging from 64 to 160 nm ($s = 4, 6, 8, \text{ and } 10$). The RBD band centers spanned the wavelength range between 2.062 and 2.398 μm .

The 76 RBD images of the Cuprite area were examined visually and statistically. About twenty images, involving five unique band positions, showed some absorption character. Four of the five absorption bands (wavelengths: 2.126, 2.174, 2.206, and 2.254 μm) can be readily explained by the known mineralogy of the study area. The remaining feature, located at 2.110 μm , may be atmospheric in origin.

The mean DN, standard deviation, and coefficient of variation of each RBD image was calculated and compared with the visual results. RBD images that showed large areas of absorption were characterized by high mean DNs, and large standard deviations. On the other hand, RBD images that contained only small areas of absorption were not statistically distinct from images that completely lacked absorption. A classification procedure is currently being developed to automatically segregate RBD images that exhibit mineral absorption features from those that do not.

Perhaps the most intriguing use of RBD images is to identify areas on the ground that are spectrally featureless at all wavelengths. Dividing the raw spectrum of such an area into each pixel in an imaging spectrometer scene should remove atmospheric absorption and solar radiance effects in the data. This RBD normalization procedure is currently being compared with a calibration procedure that utilizes actual spectral measurements of a playa in the Cuprite study area. If, as expected, the RBD procedure compares favorably, RBD images may provide a basis for calibrating imaging spectrometer data to percent reflectance even when spectral measurements of a known ground target are unavailable.

IRON MINERAL REFLECTANCE IN GEOPHYSICAL AND
ENVIRONMENTAL RESEARCH IMAGING SPECTROMETER (GERIS) DATA

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SUMMARY

This research evaluates the ability to discriminate the ferric iron minerals hematite, goethite, and jarosite using high spatial and spectral resolution image data. The discrimination of these minerals is important for a number of reasons. Iron minerals are a major constituent of soils and rocks at the surface because the weathering of iron minerals such as magnetite and pyrite leaves relatively insoluble ferric iron minerals. The spatial distribution of these minerals is related to the intensity and type of hydrothermal alteration, and they also appear to be associated with the distribution of ore minerals.

Sensors, like the Airborne Geophysical and Environmental Research Imaging Spectrometer (GERIS) and the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS), measure continuous spectra throughout the 0.4 to 2.5 μm region of the spectrum. The entire continuous spectrum is used to extract information about the depth, width, location, and asymmetry of mineral absorption features. Image processing of this type of hyperspectral data requires new approaches. Some of the techniques developed at the University of Colorado at Boulder and the United States Geological Survey in Flagstaff that were evaluated include;

1. Spectrum Differencing
2. Continuous Spectrum Ratios
3. Binary Encoding
4. Spectral Slope Encoding
5. Spectral Unmixing

GERIS data acquired for sites at Cripple Creek, Colorado and Cuprite, Nevada measure radiance in 63 contiguous spectral bands. Field reflectance spectra were measured and used to correct the image cubes to reflectance. X-ray diffraction measurements and laboratory reflectance spectra were analyzed for many of the field samples to positively identify iron minerals. The results of this study indicate that hematite and goethite can be discriminated and identified, but further work is required to resolve jarosite from goethite.

REFLECTANCE SPECTRAL RESPONSE OF AN ULTRAMAFIC INTRUSIVE IN LANDSAT TM
AND GEOPHYSICAL ENVIRONMENTAL RESEARCH (GER) AIRBORNE SCANNER DATA

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SUMMARY

Field and laboratory spectroradiometer studies show that a discrete intrusive of serpentinised peridotite, situated 60 kms east of Kalgoorlie (in the Yilgarn area of Western Australia) has distinct diagnostic absorption minima at 2312 and 2895 nanometres. Spectra were obtained from drill core, weathered rock and residual soil within the intrusive, and from background areas: they indicate that this absorption signature is unique to the area of the intrusive. Furthermore, these spectra show that these minima, though attenuated, are easily distinguishable in samples of weathered rock and residual soil from the surface.

The ultramafic intrusive cannot be located as a distinct feature on aerial photography or standard colour composites of Landsat TM imagery. However, after processing of the TM imagery to produce a colour composite where:

red	displays a negative residual band 7 prediction (to remove vegetation effects)
green	a band 4/3 ratio
blue	a band 5/4 ratio

this ultramafic is distinctly highlighted in purple.

This indicates absorption in the 2008 to 2350 nanometre and 630 to 690 nanometre regions, i.e., TM bands 7 and 3; and so this colour can be interpreted as an area which is relatively poor in iron with absorption due to the presence of hydroxyl bearing minerals and vegetation. Field checks and the results of the spectroradiometer studies confirm this interpretation. Unfortunately, areas with a similar absorption in TM band 7 (clay band 2008-2350 nanometres) will give a similar signature and so TM imagery cannot be used to uniquely locate such ultramafic intrusives in this region.

GER airborne scanner imagery with a 15 m pixel size has been obtained over this ultramafic. Several image processing techniques when applied to this imagery do distinguish the ultramafic from its environs. The most useful technique proved to be log residual processing as described by Green et al. After log residual processing of the imagery, it is possible to select bands for display in colour composites, based on the known spectral response of the rocks and soils within the area, which distinguish the ultramafic uniquely. It is also possible to map variations within the

ultramafic, for example, there are talc-rich shear zones which cross this ultramafic which can be distinguished in the log residual colour composites.

At the present time, direct correlation of pseudo spectra derived from the GER scanner imagery with spectra obtained from the spectroradiometer remains somewhat problematic.

The ability to locate ultramafic rocks and talc-rich zones, after suitable image processing of both TM and high resolution airborne scanner data, is of economic significance due to the frequent association of gold in these rocks in the Yilgarn. However, from this study, it is obvious that the high spectral resolution obtained from the GER airborne scanner is necessary if the definite identification and subdivision of ultramafic rocks in this region is to be achieved by remote sensing techniques.

QUANTITATIVE LITHOLOGIC MAPPING IN SPECTRAL RATIO FEATURE SPACE:
VOLCANIC, SEDIMENTARY, AND METAMORPHIC TERRAINS

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SUMMARY

The nature of spectral lithologic mapping was examined using ratios centered around the wavelength means of Landsat Thematic Mapper imagery. Laboratory derived spectra were analyzed in order to determine the two-dimensional relationships and distributions visible in spectral ratio feature space. Laboratory spectra of silicates, oxides and hydroxides, sulphides and sulphates, and carbonates, were plotted as a function of two ratios ((0.66 μm /0.485 μm) vs. (1.65 μm /2.22 μm)).

The spectral distributions of these rocks and minerals in ratio feature space were found to be controlled by several spectrally dominant molecules. Three distinct distributions were identified in this ratio combination:

Silica (SiO_2), Iron-Iron Oxide (Fe, FeO), and hydroxyl or free water molecule (OH, H_2O); with each having distinct spectral end members.

Using Landsat Thematic Mapper data, the same ratio combination was examined over arid to semi-arid areas with little or no vegetation cover. The satellite imagery was radiometrically calibrated and atmospherically corrected and converted to reflectance.

Four study areas were selected that contained spectrally representative samples of volcanic, sedimentary, and metamorphic rocks: Rawhide Mining district; Nevada; San Ysidro, New Mexico; Manzano Mountains, New Mexico; and Sevilleta LTER site, New Mexico. In the (0.66 μm /0.485 μm) and (1.65 μm /2.22 μm) plot, the distribution of rock classes was once again found to be controlled by the dominant molecules of silica (SiO_2), Iron and Iron Oxide, and the hydroxyl or free water molecule. Using the distribution of these rock classes, detailed geologic maps were constructed for the various study areas. The limits of lithologic mapping using ratios and Thematic Mapper data are examined.

The separability of rock classes, spectral mixtures and end members, as well as the addition of vegetation cover are discussed in detail as applied to geologic mapping in volcanic mineralized zones and in sedimentary basins.

COMPARISON OF THE CAPABILITIES OF THE JAPANESE EARTH RESOURCES
OPTICAL SENSOR AND THE LANDSAT THEMATIC MAPPER FOR LITHOLOGIC MAPPING

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SUMMARY

Given the uncertain future of the Landsat system, alternative spaceborne visible and near-infrared (VNIR) and short-wavelength infrared (SWIR) imaging radiometers may be required during the 1990's to meet the needs of exploration geologists. An imaging system, termed the Optical Sensor (OPS), will be carried aboard the first Japanese Earth Resources Satellite (JERS-1), scheduled for launch in 1992. The OPS is an eight-band "pushbroom" system, with detectors measuring radiance in the wavelength ranges 0.52-0.60 (band 1), 0.63-0.69 (band 2), 0.76-0.86 (bands 3 and 4), 1.60-1.71 (band 5), 2.01-2.12 (band 6), 2.13-2.25 (band 7), and 2.27-2.40 μm (band 8). Band 3, which is nadir-viewing, and band 4, which is forward-viewing, will provide complete and virtually simultaneous stereoscopic coverage with a stereo angle of 15° and a resulting base-to-height ratio of 0.3 (corresponding to a vertical resolution of approximately 60 meters). The ground resolution of the system will be 18 x 24 meters and the swath will be 75 kilometers.

The OPS system could be of particular benefit for discerning mineralogic differences associated with ore mineralization because of the three bandwidths in the range 2.0 to 2.4 μm , as compared to the single Landsat Thematic Mapper band in this wavelength region (TM band 7). Numerous alteration minerals (e.g. clays, sulphates, carbonates) have characteristic absorption features in the range 2.0 to 2.4 μm that can be resolved by the three OPS bands. However, the added benefit of the increased spectral resolution may be minimized by decreased radiometric resolution; as presently designed, the OPS quantization level for all eight bands on JERS-1 will be 6 bits (64 grey levels), as compared to 8 bit Thematic Mapper data (256 grey levels).

An analysis of the potential of the OPS system for mineralogic differentiation has been done by converting radiance, reflected from various surface targets, to expected Digital Number (DN) output for the OPS bandwidths. Solar irradiance, atmospheric transmissivity, atmospherically-scattered indirect illumination, surface reflectivity, maximum radiance at detector saturation, and signal-to-noise ratio are included in the modelling for each of the bandwidths. Analogous modelling has been done for the Thematic Mapper system to determine DN output for the TM bandwidths. Laboratory measurements of reflectance from mineral powders or fresh surfaces, and from rock weathered surfaces were used as the input surface reflectivities. Classification of the resulting DN values by a supervised minimum-distance to class means algorithm was done to evaluate the relative abilities of the OPS and TM systems for lithologic discrimination.

Two cases were evaluated: 1) discrimination of minerals associated with hydrothermal alteration of silicic rocks (kaolinite, montmorillonite, alunite, calcite), and 2) discrimination of

metamorphosed and altered basalts produced by hydrothermal circulation of seawater through oceanic crust (i.e. the source of massive sulfide "black smoker" deposits). The basalt samples are from ophiolite exposure in the Brooks range, northern Alaska, where subtle spectral variations in TM images have been used to map mineralogic differences related to hydrothermal metamorphism and alteration. OPS bands 6, 7, and 8 are effective in differentiating kaolinite, montmorillonite, alunite, and calcite due to the pronounced absorption features present in the reflectance spectra of the powders and fresh surfaces in the wavelength range 2.0 to 2.4 μm . TM band 7 alone cannot differentiate these minerals. However, the OPS, using all bands, is significantly less effective than the six VNIR and SWIR TM bands in differentiating the basalt weathered surfaces because the DN variations induced by noise (using design specifications for the OPS) are comparable in magnitude to the DN separation of the basalt classes achieved by the OPS.

WEATHERED AND UNWEATHERED ROCK SURFACES:
DIFFERENCES IN SPECTRAL PROPERTIES AND REMOTE SENSING IMPLICATIONS

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SUMMARY

As part of a comprehensive evaluation of reflectance spectra for remote sensing geological mapping, a suite of representative Canadian Shield rocks were examined in the laboratory. In most cases a weathered and unweathered interior sample were characterized in order to search for spectral variations which accompany the weathering process. An additional aim was to evaluate whether pristine sample spectra are acceptable representatives of weathered surfaces. The samples examined include basalt, greywacke, schist, iron formations, granite, and volcanoclastics.

Data analysis is still in the preliminary stages but a number of criteria separating weathered from unweathered sample spectra have been identified. In general, unweathered sample spectra are characterized by fewer absorption bands, and shallower, bluer slopes (i.e. less increase or actual decrease in reflectance towards longer wavelengths). Beyond these differences, there appears to be little consistency between weathered and unweathered spectra of the same sample. In some cases spectral differences are most evident in the ultraviolet and visible regions and nearly identical at longer wavelengths, while in others the spectra are radically dissimilar.

When the weathered and unweathered reflectance spectral of the same sample show similar overall appearance, the absorption bands are often found at slightly different wavelengths, and have different shapes and intensities. The sometimes dramatic differences between unweathered and weathered spectra suggest that the low weathering rates prevalent in high-latitude and alpine regions are sufficient to significantly alter the mineralogy of the optically sampled zone.

The greater amount of detail in weathered spectra will facilitate the extraction of more, and more accurate, mineralogical information than is possible from unweathered spectra. The current thrust of this research program is to search for systematic variations in spectral properties which can be used to relate the weathered spectra, which would be imaged by remote sensing systems, to the underlying, more pristine mineralogy of the subsurface. The reflectance spectra of the unweathered surfaces are often devoid of well-defined absorption bands, in spite of the sometimes complex mineralogies of the samples. Powdered samples may be required for sufficient spectral contrast to resolve the expected absorption bands.

The spectral differences between weathered and unweathered surfaces are significant enough that the latter may not be usable for the analysis of remote sensing spectral data of exposed rock units. Further work is being undertaken to determine whether correlations can be developed to relate unweathered to weathered rock spectra, and applied to remote sensing data analysis.

LANDSAT EXPRESSION OF PRECAMBRIAN STRUCTURAL FEATURES --
EXPLORATION IMPLICATIONS OF "SEEING THROUGH" THE SEDIMENTARY COVER

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SUMMARY

The Precambrian crystalline basement consists of a mosaic of structural blocks which reflect the plate tectonic assembly of the continental lithosphere. Phanerozoic reactivation of these Precambrian structural features controlled deposition of the sediments overlying the basement, formation of structures within the sedimentary layers, and development of surface features marking the Precambrian structures. Three study areas in central Minnesota, west-central South Dakota, and northeast Montana serve as case studies to document the correspondence of basement structures with surface features visible on Landsat.

Plate tectonic interpretation of the Precambrian basement have become increasingly sophisticated in the past decade. All three study areas are situated on a Proterozoic convergent margin, but have different thickness of sedimentary cover. In central Minnesota, the Penokean Orogen is covered by generally less than 500 ft (152 m) of glacial sediments. In west-central South Dakota, the eastern margin of the Trans-Hudson Orogen and the northern margin of the Central Plains Orogen are overlain by predominantly Mesozoic sediments less than 3,000 ft (912 m) thick. In northeast Montana, the western margin of the Trans-Hudson Orogen is overlain by more than 10,000 ft (3,040 m) of Paleozoic and Mesozoic rocks. All multispectral scanner images employed in these areas were standard EROS film products in black and white format at scales of 1:1,000,000.

Linear features are the most obvious surface features visible on Landsat which correspond with specific Precambrian structures. The linear features are also used to interpret lineament zones which mark large basement features. In central Minnesota northeast-trending faults which bound a complex of Proterozoic thrust duplexes and north-northwest faults which trend oblique to the orogen are marked by individual linear features. In west-central South Dakota, the north-south margin of the Archean Superior Province corresponds with a Landsat lineament and several northeast faults which trend oblique to the Proterozoic orogen correspond with specific Landsat linear features. In northeast Montana, the western margin of the orogen generally trends north-south, but includes promontories and indentations in the Archean Wyoming Province which are reflected in Landsat lineaments trending northwest and northeast. Each study area has a different thickness of sedimentary cover and as a consequence exploration objectives are different.

Central Minnesota has mineral resource potential, although there is no current production. Exploration for diamonds is currently underway along one of the Landsat lineaments, although remote sensing was probably not employed to identify objectives. West-central South Dakota has potential for shallow gas, but has not current production. Exploration for groundwater and for geothermal resources has successfully employed Landsat lineaments. Northeast Montana is an area of oil and gas production; oil field locations and gas pressure patterns correspond with Landsat lineaments. Although our understanding of the Precambrian structural complex is less clear in areas of thick sediments, recurrent paleotectonism has made Landsat lineaments attractive targets for resources in the sedimentary cover. In areas of thin cover, Landsat features mark Precambrian structures of interest for mineral resources.

PRELIMINARY ASSESSMENT OF JERS-1 OPTICAL SENSOR
BASED ON THE SIMULATED AIRBORNE DATA

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SUMMARY

One of the outstanding characteristics of Japanese ERS-1 is a geologically oriented architecture, which is featured by four independent bands in the SWIR region of the optical sensor. Band configuration in the SWIR region is expected to help discriminate details for alteration mapping.

A high-resolution airborne multispectral scanner of GER, covering the wavelength between 500 and 2,500 nm with 63 channels, was employed for a preliminary assessment of spectral performance of the SWIR bands based on the simulated images from the airborne data prior to the scheduled launch of JERS-1 in 1992. The Yerington area in Nevada was selected for a test site as its diversity in terms of alteration is optimum for the assessment of the designed SWIR bands. The study includes digital processing to produce simulation images, and interpretation and assessment of the images by field verification work.

The original data acquired have to go through several stages of primary calibration and data reformatting prior to image processing. These calibrations include dark current correction to remove electronic striping effects, time constant correction to remove the lag effect caused by electronics response time, roll correction to remove the aircraft roll effects, and subsequent conversion of the instrument counts to radiance. Radiance data processed are synthesized into the individual JERS-1 bands.

Several kinds of simulated images were produced to allow correlation with field information as well as with the results of minerals identification based on the airborne data processed by the logarithmic residual method. Band configuration in the SWIR region is anticipated to be useful for classifying the alteration minerals into three groups based on the sharp absorption features alunite, pyrophyllite, kaolinite around 2.16 μm , kaolinite, montmorillonite around 2.20 μm and calcite, dolomite, epidote, chlorite around 2.33 μm .

Consequently, alunite seems to be discernible from surrounding montmorillonite in the decorrelation-stretched false color image of band 6, 7 and 8. Moreover, chlorite, epidote, and/or calcite have been identified in the ratio image of 5/7, 5/6, and 5/8. The study result has demonstrated the possibility that SWIR bands of JERS-1 could provide useful information for minerals exploration in terms of alteration mapping.

IS AIRBORNE DIGITAL IMAGERY A USEFUL EXPLORATION TOOL?

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SUMMARY

The Programmable Multispectral Imager (PMI) has flown over an active exploration site in Northern Ontario to collect spatial and spectral data at resolutions higher than those currently available by satellite. The programmable nature of the imager allows band and width selection and the mapping of variations in vegetation reflectance due to stress. By selecting the optimum band set and integrating geophysical, geochemical and forestry data, subsurface geological features and geochemical anomalies have been delineated. The results from the project demonstrate that not only the changes in spectral response from vegetation can be mapped, but when combined with simple imagery analysis techniques, and other digital data, they can be applied as a valid exploration tool.

SPECTRAL REFLECTANCE OF GABBROIC ROCKS FROM CANADIAN TERRAIN

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SUMMARY

Gabbroic rocks are of economic significance in mineral exploration programs as they host platinum group minerals, sulphides and other minerals. An understanding of their spectral reflectance properties will enable explorationists to use spectral reflectance measurements as a mineral exploration tool.

Gabbroic rocks selected from various sites in Canadian terrain (Ontario) were subjected to spectral measurements using the SPECTRON SE590 Portable Data-Logging Spectroradiometer and the Barringer REFSPEC Reflectance Spectrometer. The SPECTRON Spectroradiometer reads in the range from 350 nm to 1100 nm. The REFSPEC reads in the range from 450 nm to 2450 nm. Gabbros, leucogabbros and gabbroonorites were subjected to spectral reflectance measurements. Rocks with fine to coarse-grained surfaces rocks with and without FeO staining and powdered rocks were measured. The results indicate that in gabbroic rocks, FeO staining does not change the essential absorption features. Absorption features in a coarse-grained, medium-grained and fine grained rocks show no essential differences. The exception is gabbroonorite which showed a diminished absorption feature in the fine grained sample at 900-1000 nm.

These results of gabbroic rocks measured in a laboratory are preliminary to field studies in an exploration program. If mineralogy can be determined to be associated with a particular gabbroic rock type whether non-weathered or weathered and a particularly textured gabbroic rock type, then this method can be used to locate mineralogically associated gabbroic rocks.

**THE GULF OFFSHORE SATELLITE APPLICATIONS PROJECT:
IMPLICATIONS FOR OFFSHORE PETROLEUM EXPLORATION**

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SUMMARY

Petroleum exploration in frontier areas requires synoptic wide area coverage both onshore and offshore. While onshore petroleum exploration using remote sensing techniques has become nearly routine, many of the remaining potential oil provinces lie offshore at shallow to moderate water depths.

The Gulf Offshore Satellite Applications Project (GOSAP) is being undertaken by members of the petroleum and marine industries under the auspices of the Geosat Committee to determine how best to use remote sensing to address practical problems faced by these industries. Primary among these objectives, the GOSAP team will evaluate the potential for satellite offshore exploration using combined satellite and "sea truth" data sets.

The exploration objectives of this 2-5 year study will compare sea surface spectra from satellites (ERS-1, Radarsat, SPOT, Landsat) with water column and sea floor measurements from instrumented fixed and mobile platforms in the Gulf of Mexico with the aim of establishing repeatable correlations between surface and sea floor.

Test sites will be selected over known oil fields in the Gulf of Mexico occurring at shallow to moderate water depths and extensive measurements will be taken above, at, and below sea surface to determine how best to image the sea floor or detect oil seeps from orbital altitudes.

The potential correlation of satellite-collected sea surface signatures, oil seeps, and sea floor geology will enable explorationists to extend these techniques into frontier areas.

The project will involve cooperation between government agencies, industry, and universities who will each contribute to the data collection image processing or interpretation phases.

SUCCESSFUL APPLICATIONS OF REMOTELY SENSED DATA IN MATURE BASINS

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SUMMARY

In addition to the traditional reconnaissance role played in frontier basins, MSS and TM satellite data has been used with success in mature basins to locate minor low-relief buried structure, minor faulting and related fracture systems, and sometimes geochemically altered surface rocks and soils resulting from hydrocarbon microseepages.

Once this information has been obtained from the satellite data, it is then necessary to follow up with detailed subsurface geology, seismic, other geophysical tools, and geochemistry in order to develop a drillable prospect model. Two or more examples of the successful use of this approach to the use of this technology are presented.

STRUCTURES IN THE SHILLONG PLATEAU RELATED TO THE
NINETY-EAST RIDGE IN THE INDIAN OCEAN

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SUMMARY

The Shillong plateau forms a part of the north-eastern extremity of the Indian peninsular shield. The upland plateau consists of dominantly Archean gneissic complex and Proterozoic metasedimentaries.

A few nearly N-S trending and extensive lineaments have been observed on the Landsat images and aerial photographs of the Shillong plateau. These lineaments traverse across the strike of the Precambrian rocks and are definitely post-Precambrian. One of these major zones is the Um Ngot lineament. This zone is found to encompass the Sung Valley Complex, an intrusive body of alkaline-ultramafic-carbonatite suite, which is indicated to be of Cretaceous age by fission-track dating. Several similar circular bodies are also detected on the Landsat images in this lineament zone. These bodies are marked by relatively poor vegetation, in a terrain of general dense vegetation, owing to geobotanical attributes. Further, in another adjoining area, some N-S trending major lineaments have been observed and field reports also indicate the presence of carbonatite suite of rocks in this area.

On a synoptic scale, the Shillong plateau is found to lie in direct continuation of the Ninety-east Ridge, an important N-S trending lineament in the Indian Ocean. Geophysical, petrologic, and ocean drilling data from other works suggest that the Ninety-east Ridge formed as the trace of the Kerguelun hot-spot on the Indian plate, as the Indian plate drifted northwards. Radiometric data along the Ninety-east Ridge indicate successively older rocks towards north. The plot of ratios of incompatible elements from Sung Valley Carbonatite in the Shillong Plateau lies in close proximity to the trend shown by the Ninety-east Ridge basalts.

It is inferred that the N-S trending lineaments and the associated carbonatite suite of rocks in the Shillong plateau are genetically related to the Ninety-east Ridge in the Indian ocean. Integration of earlier available geophysical, petrologic and radiometric data, new information from Ocean drilling and our Landsat and field data, leads to a coherent picture on deep basement structures and tectonic evolution of the area.

APPLICATION OF A FIELD PORTABLE THERMAL INFRARED
SPECTRORADIOMETER TO SUBSURFACE PLUME DETECTION

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SUMMARY

Theoretical research involving extensive computer modelling of the likely response of surface soils and vegetation to solar irradiation and subsequent emission in the Thermal InfraRed (TIR) wavelength region showed, in agreement with previous workers, that various subsurface targets could be theoretically detected by a remote sensor. The modelling did not include atmospheric effects upon returning radiation. Of particular interest was the possibility of detecting subsurface plumes which may emanate from a landfill site.

In order to test the theoretical work a TIR calibrated spectroradiometer (dubbed THIRspec) was designed, constructed and tested. It features a 60-element HgCdTe linear array detector, and a closed cycle Stirling engine cooler. A small, 1 kg microprocessor controller/data logger provides five hours of operation per battery charge, with considerable built in programming and user transparent communication via an RS-232C port. A fixed plane grating disperses the 7.7 to 11.75 micrometre spectrum across the array. Energy calibration is achieved by accurate measurement of the temperature of a carefully designed black body contained in THIRspec's optical head. Each resolution element is 0.067 micrometre, more than adequate for the study reported here, but which also allowed study of subtle spectral emissivity variations in the 8.5 to 11 micrometre region of aluminosilicate soils and rocks in the field study area.

Results obtained using THIRspec in the field are presented. Results are also discussed and a comparison with theoretical results for modelled terrain presented together with comments on their pertinence to other areas of TIR investigation, particularly the likely effect of vegetation on the surface measurements are reported.

SAR-LANDSAT TM-GEOPHYSICAL DATA INTEGRATION:
UTILITY OF VALUE-ADDED PRODUCTS IN GEOLOGICAL EXPLORATION

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SUMMARY

Digital integration of SAR, Landsat TM and geophysical data was performed for mining and oil and gas exploration. The two areas under study are located in Alberta and Ontario, and cover four 1:50 000 topographical sheets each.

Airborne SAR, spaceborne Seasat SAR and Landsat TM imageries were geometrically corrected to be registered with gravity and aeromagnetic data. Simple polynomial transform was used for airborne SAR and Landsat TM rectification. However, because of severe relief geometric distortions of SEASAT data, digital elevation model was produced and integrated for the rectification.

Various types of enhancements were performed: modulation of radar data by Landsat TM data, HSI transformation of SAR with Landsat TM or vertical magnetic gradient data, stereoscopic and perspective viewing of SAR imagery where the parallax generated comes from the magnetic or the gravity field.

These value-added products generated were found useful in the display of the correlation between surface and underneath geological features and, the following, in the on-going field investigation. In particular, the addition of planimetric information extracted from Landsat TM data to SAR data reduces the ambiguity in lineament interpretation when related to human activity. Otherwise, HIS transform shows high correlation between linear features observed on SAR data and aeromagnetic discontinuities.

AN INTERPRETATION OF RADAR AND LANDSAT THEMATIC
MAPPER IMAGES OF CORNWALLIS ISLAND, NORTHWEST TERRITORIES

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SUMMARY

Cornwallis Island is located in the Canadian High Arctic (75° North Latitude) in an area that is being actively explored for base metals and for hydrocarbons. The Island is largely underlain by tectonically deformed Paleozoic, Mesozoic and Cenezoic sedimentary rocks.

This study compares the information content of a digitally mosaicked airborne radar survey and a Landsat Thematic Mapper (TM) image for the detection of sedimentary and surficial rock units, for fold structures and faults, and for mapping the terrain morphology.

To accomplish this, the airborne radar mosaic and the Landsat scene have been coregistered and processed using both image analysis and GIS techniques. Three sub-areas have been studied in greater detail. One sub-area displays varied relief, another includes many of the folded and faulted rock units, while the third contains widespread surficial deposits and their associated moisture patterns.

The radar mosaic can be used to map nearly all of the folds and faults that appear on a recently published geological map. Many of the carbonate units, being relatively resistant to erosion, and so better exposed, can be recognised by the smoother weathered surfaces that results in lower radar backscatter values. The side-looking radar presents a 'shaded relief' view of the terrain that is particularly suitable for mapping most of the faults and many of the rock units. The relief map can also be used here to determine the sense of dip of the folded sediments.

The enhanced TM images provide a better definition of outcrop, of glacial overburden and layering within rock units, but contain less structural detail.

INTERFEROMETRIC RADAR --
A BETTER TOOL FOR EXPLORATION GEOLOGY?

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SUMMARY

Airborne synthetic aperture radar (SAR) is a powerful tool for exploration geology because it is sensitive to changing terrain slope and terrain type. Unfortunately, there are distortions in SAR imagery associated with variations in terrain elevation which can be difficult to remove without a digital elevation model. Secondly, one cannot measure slope directly from airborne SAR data. While stereo SAR can be used to estimate terrain elevation, the process is expensive, relatively complex, and the results are limited in accuracy.

Although the radar system becomes more complex, interferometric SAR data can be used directly to obtain terrain elevation and slope information and to remove the resulting image distortions. Both interferometric and normal image data can be collected simultaneously in any weather, the baseline is fixed and known, and the stereo correlation step is avoided.

The Canada Centre for Remote Sensing owns and operates X- and C-band, dual channel, dual polarization SAR systems on a Convair 580 aircraft. This paper describes the results of a feasibility study whereby one radar would be modified to operate in an interferometric mode. By offsetting a second receive antenna in the cross-track plane, it is possible to measure the phase difference of the two receive signals. The method by which differential phase is transformed to terrain elevation information is outlined and the sources of error identified and discussed.

A computer simulation has been carried out to model and illustrate the main sources of error in terrain elevation estimation. Analysis of receiver noise, baseline speckle, and aircraft motion induced errors suggests that elevation accuracies in the range of 5 - 10 m rms should be obtainable from the CCRS radar. As well as a description of the feasibility study, a summary of the progress in implementation will be presented.

It is hoped therefore, that interferometric SAR will not only detect geological features, e.g. lineaments, but also be used for planimetric and elevation mapping to an accuracy not achieved previously by SAR surveys.

ORBITAL IMAGING RADAR OF THE CANADIAN SHIELD:
EXPERIENCE FROM SIR-B AND SEASAT

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SUMMARY

This paper summarizes results and implications of the first use of orbital imaging radar for geologic investigations of the Canadian Shield. Two joint Canadian-American experiments were carried on the 41-G Shuttle mission in 1984, intended to use Shuttle Imaging Radar (SIR-B) to study crustal province boundaries and other features. The imagery from this mission was used, together with Seasat and airborne C-band imagery simulating orbital illumination, for structural investigations of fracture patterns and dyke swarms, the structure of the Sudbury Basin, and for technique development. Geologic results have been presented elsewhere (Masuoka et al., 1989; Lowman, 1989). The broad implications of this work for future Shield studies are the following: (1) Orbital radar can produce valuable structural information not matched by equivalent Landsat imagery if suitable illumination geometry is used. (2) No one pass with orbital radar can give adequate coverage of most areas because of illumination azimuth biasing and the need for multiple incidence angles. (3) Digital enhancement techniques are necessary for optimum use of imagery, both to increase contrast and to combine multiple look directions or data sets. (4) Future orbital radar programs such as Radarsat, ERS-1, and SIR-C will increase our knowledge of Shield structure, but adequate radar coverage will take many years to acquire.

CORRELATION OF SIR-B IMAGERY WITH LITHOLOGY IN WEST CENTRAL NEVADA

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During October of 1984, NASA's Space Shuttle Mission 41-G collected several passes of overlapping radar imagery in western Nevada as part of the SIR-B (Shuttle Imaging Radar-B) experiment. The Analytic Sciences Corporation (TASC) has used this data to demonstrate a new quantitative method for lithologic discrimination. Conceptually, the technique is designed to remove the topographically driven portion of the radar return, enhancing the fraction associated with surface roughness and dielectric constant. The hypothesis is that different lithologic units have fractured or weathered in characteristic ways, or have sufficiently different chemistry and water content, so as to make them distinguishable at the 23.5 cm wavelength of SIR-B.

The correlation technique employed requires that the SIR-B imagery be accurately registered to high quality (Level 2) digital terrain data, so that the local incidence angle for each radar pixel can be calculated. Using the multi-pass coverage (with a broad range of regional incidence angles), the radar backscatter for each pixel is then estimated as a function of local incidence angle. By aggregating data for small areas having the same lithology, good statistical estimates of backscatter curves for various lithologies represented in the imagery can be obtained. These curves could, in principle, provide the basis for automated classification of multi-pass radar imagery outside the area used for training.

A variety of technical difficulties during the mission prevented the collection of both the quality and quantity of data required for the intended analysis. Nevertheless, the imagery afforded the opportunity to investigate the concept and to understand better the information content of L-band SAR imagery. To test the methodology, Landsat Thematic Mapper data has been used in conjunction with published geologic maps and field reconnaissance to define test areas comprising known, consistent lithologies. Several sites in west central Nevada have been used; all are to the west northwest of Tonopah, in the vicinity of Garfield Hills, Excelsior Mountains, and the Candelaria Hills. The actual SIR-B acquisitions limited the lithologic diversity to Mesozoic intrusives, Tertiary volcanics, and several Quaternary alluvial and playa deposits.

Estimates for the SIR-B backscatter from the fundamental lithologic units in the test area are presented in this paper along with a more detailed discussion of the methodology. In addition, this investigation has led to the development of several new image processing techniques, especially in the areas of image registration and noise filtering. Because of uncertainties in the SIR-B calibration, extension of the backscatter results to other areas is probably inappropriate. The lithologic correlations described and an associated analysis of backscatter quantization error should, however, be significant to those planning experiments for SIR-C and other radar missions.

INTEGRATED IMAGING EXPERIMENT WITH C-SAR AND OTHER
GEOLOGICAL IMAGE DATA ACROSS THE NELSON FRONT, NORTHERN MANITOBA

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SUMMARY

Airborne C-SAR (nadir and narrow swath mode) experiment was carried out in August 1988, across the Nelson Front in northern Manitoba, with objectives of studying the preCambrian geological province boundaries and developing techniques for the geological use of airborne radar. The surface swath of this experiment in general follows that of the L-band SIR-B (NASA) experiment of 1984. Other geological image data include surface geological map, Landsat MSS and TM image and airborne magnetic data.

Some of the major objectives of this experiment include evaluation of the scientific usefulness of airborne C-SAR data in geophysical imaging, investigation of effectiveness of integrated Landsat and radar data with geological data and evaluation of illumination azimuth and polarization effects in the low-relief Canadian shield environment.

The preliminary results indicate that the optimum incident angle for geological application for this test area appears to be much greater than those suggested for other geological terrains in the Canadian shield, the geological structural features appear most prominent when the illumination azimuth forms an angle within about 20° of the perpendicular to the local structural trends, and the effects of HH and VV polarization for this low relief test area are not very significant.

Along the Nelson Front (Churchill - Superior Boundary Zone), the ground expression is extremely low relief and any meaningful geological interpretation requires additional

enhancement using other geological and geophysical data. However, along the Wekusko Lake area, the structural rendition of surface geology is excellent.

EXAMPLES OF RADAR IMAGERY FOR QUATERNARY GEOLOGICAL
MAPPING IN GLACIATED TERRAINS

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SUMMARY

Quaternary geological maps produced by the national and provincial geological surveys are the main source of information on surficial materials, glacial history and stratigraphy in Canada. Aerial photography is routinely used for delineating terrain types and surficial units. Satellite images are used, where appropriate, for the regional mapping of geobotanical associations and regional terrain typing. To date, the use of radar images for Quaternary mapping in Canada has been limited. This study examined the value of airborne radar images for Quaternary mapping over sites in Ontario and Manitoba representing several types of glaciated terrain.

The RADARSAT Project Office of the Canada Centre for Remote Sensing acquired airborne C-HH and X-HH SAR data of the sites. An altitude of 20,000 feet was used to produce a spatial resolution of 6 x 6 metres. Some sites were flown with the radar sensor set for a narrow coverage swath (approximately 18 km) and depression angles of from 14 to 45 degrees. Other sites were flown in nadir mode, with a swath of approximately 22 km and depression angles of from 16 to 90 degrees.

Interpretation of the radar images has provided considerable information on Quaternary landforms and surficial materials, as well as insights into the glacial history of some of the sites. For example, over a site near Sudbury in northern Ontario, the style of deglaciation and conditions occurring subglacially and beyond the ice margin were interpreted from the shape and distribution of the landforms and the relationship among them. Here, a "classical" esker-fed ice marginal delta, formed along a wave-cut end-moraine, attested to the presence during glaciation of high-level ice-contact lakes, glacier-fed, in the Sudbury basin. At a site near Geraldton in northern Ontario, esker-outwash complexes, fluted terrains and areas of thin and thick drift were delineated and mapped on the C-band radar images. In southern Ontario, surficial units were delineated from combinations of spring C-band and X-band images and enhanced TM data, on the basis of the radar response to the moisture content and texture of the surficial materials. At a vegetated site near the Pas in northern Manitoba, a combination of C-band and enhanced TM data was found to provide more information on surficial materials and landforms than the radar imagery itself.

ANALYSIS OF TIMS INFRARED DATA OF MT. ETNA, SICILY (ITALY)

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SUMMARY

In the framework of a cooperation between NASA/JPL and CNR/IAS, an airborne remote sensing campaign has been carried out in July 1986 by means of the NASA Land Survey C130B aircraft over the active volcanic regions of southern Italy. Data were collected by different multispectral sensors operating in the visible, near-infrared, mid-infrared and thermal infrared spectral ranges. In particular, thermal infrared data have been proven to be very useful for discriminating between different lithological units, because slight shifts in silica content produce differences in the spectra characteristic of the thermal bands.

In this work we focus our attention on the Thermal Infrared Multispectral Scanner (TIMS) data of Mt. Etna, a 3323 m high shield volcano located in the eastern side of Sicily. We have processed and analysed TIMS images: 1) to yield image data in cartographic projection to be used for thematic mapping and 2) to discriminate among the different lava flow units to produce a volcanologic map based on the thermal characteristics of the surface materials.

The TIMS is characterized by 6 channels that record the emitted energy of Earth surface in the 8 to 12 microns spectral range. In addition to TIMS data, also Thematic Mapper Simulator data have been collected. The image data have been recorded along six diurnal flight lines, intersecting over the summit caldera of Mt. Etna at an altitude of about 7300 m. The pixel ground resolution is a function of the surface topographic relief, ranging from 10 to 20 m.

The image processing procedures we adopted include: radiometric and atmospheric corrections, correction of the geometric distortion due to the scanning system, and transformation of the pictures into the UTM projection. Radiometric, atmospheric and geometric corrections have been performed by using a software developed at the JPL. UTM projected images have been, instead, obtained by means of algorithms implemented by the authors, who calculated the UTM coordinates of each pixel of the original images and mapped the radiance values into the new reference system on the basis of some flight parameters (coordinates of the initial and final lines, flight altitude) and of a Digital Elevation Model of the surveyed area. This procedure has been necessary because it has not been possible to apply the registration methods suitable for satellite pictures, for which the very high satellite altitude makes the topographic relief of the imaged area negligible.

The six UTM rectified images have been assembled into a mosaic to obtain a digital map in which the different thermal characteristics of the lava flow materials have been emphasized.

Furthermore, in order to convey as much spectral information as possible to photointerpretation, it is important that the three bands used for false color display be not too correlated, otherwise the representation may appear monochromatic. To avoid this and since the 6 TIMS spectral channels are highly correlated, decorrelation techniques have been applied to the Mt. Etna TIMS data. The final mosaic shows enhanced subtle color differences, probably related to different ages and compositions of the volcanic materials, so providing a more detailed description of the geologic contacts with respect to that given by the traditional geological maps of Mt. Etna.

EXPLORATION FOR CONSTRUCTION MATERIALS FOR BOTSWANA ROADS

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SUMMARY

The shortage of economic deposit of suitable road building material is a serious problem in many tropical and sub-tropical environments which adds significantly to the cost of developing modern all-weather roads.

To establish priorities for routes to be improved as part of the 1986-1991 five-year plan, the Government of Botswana, in the first phase of the Botswana Feeder Roads Plan, required a cost-benefit analysis of 39 routes totaling 4000 km in length in order to select a short list of 1000 km for the preparation of detailed feasibility studies.

The 4000 kms of routes were distributed over an area of 5.5 million square kilometers of arid and semi-arid Kalahari Desert. The cost side of the cost-benefit study entailed the examination of the routes on 30 satellite images to establish the probable presence of suitable road-building material and of water for the construction process.

Over most of the Kalahari, a thick sand sheet covers bed-rock and the only available potentially suitable material is calcrete, a recent calcareous evaporite. Calcrete is associated with the margins of pans, playas, and with fossil drainage systems. It varies in quality from useless powder to hard tabular strata; the ideal form is nodular forming a natural gravel. On the standard Landsat images, available at the time of the study, the typical appearance of known calcrete deposits ranged from pale blue through blue grey to grey. Corridors 15 km wide centered on existing desert roads, were interpreted taking a traditional photogeological approach. Areas interpreted as likely to yield calcrete were linear patterns associated with former drainage systems, terraces associated with the unusual pans of the Kalahari and inter-dune depressions, especially where these features were coincident with characteristic ranges of tones.

For material availability, the routes were compared according to percentage lengths which fell into various haulage distance categories. Costs were attached to the various routes according to haulage distances from source to route. Benefits, in terms of improved access to cattle markets, schools and clinics were evaluated and related to the size of the population along each route. The routes were ranked according to the cost-benefit ratios. The Landsat image acquisition and interpretation, and the tabulation and integration of the findings took six weeks.

In phase II, the 17 shortlisted routes were interpreted in more detail using existing aerial photography followed by route inspection to produce preliminary design reports. The majority of calcrete located was confirmed but proved unsuitable; however, suitable nodular calcretes were located on terraces along the north shores of the larger pans.

The study represented an ideal situation for the application of satellite image interpretation to a consulting engineering problem. The situation comprised substantial route lengths scattered over a vast area that had negligible geologic mapping. The routes had to be evaluated and compared within tight time constraints. Indeed, the project could only have been accomplished in time with satellite imagery.

PETROPHYSICAL PROPERTIES OF THE GLAUCONITIC FORMATION
FROM PETROGRAPHIC IMAGE ANALYSIS OF THIN SECTIONS

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SUMMARY

Petrographic Image Analysis (PIA) has been performed on 77 samples from 9 wells from the Glauconitic Formation to quantify pore geometry, abundance and distribution and ultimately to calculate porosity, permeability, capillary pressure data and formation factors from thin sections. Images are acquired by a black and white video camera mounted on a petrographic microscope and converted into a 512 x 512 digitized image with pixels approximately 2.5 x 2.5 microns. Each pixel is assigned one of 256 gray level values. Image analysis was used to measure several first order parameters from polished thin sections impregnated with blue dyed epoxy. These parameters include abundance, cross-sectional area, length, width, Feret diameter and perimeter of pores. These first order parameters are then used to calculate second order parameters such as shape factors, aspect ratios, specific surface and pore size distributions. From these measurements, the fundamental petrophysical parameters of porosity, permeability, capillary pressure and formation factors are empirically derived.

To enhance the image of the pore, complex segmentation of the image is performed. Segmentation of the image into classes of gray levels is achieved by isolating the contrast in intensity of red and blue light transmitted through thin sections impregnated with blue dyed epoxy. When an image of the pores has been segmented into a black and white binary image it can be processed by digital filters such as erosion and dilation. Erosion is the process of removing the outermost layer of pixels from a pore. Dilation is the opposite of erosion. Erosion-dilation cycles can be used to analyze the size and shape of pore features within a pore complex.

Correlation between core analysis porosity and permeability for Glauconitic Formation sands and PIA porosity and permeability is high ($r = 0.81$). Capillary pressure curves calculated from PIA measurements correspond to laboratory capillary pressure curves for the Glauconitic Formation. There is good agreement particularly in the low pressure area of the curves. The area that is not in agreement could be the result of either an under estimation of the pore throat sizes in the image analysis curves, or an under estimation of the number of throats of a particular pore throat size range.

The benefit and application of PIA is that it can be performed on small samples, such as drill chips and sidewalls, laminated samples or unconsolidated samples (tar sands). It also quantifies the pore geometry systematically and can therefore give more information even on standard core and thin sections.

APPLICATION OF SATELLITE REMOTE SENSING TECHNIQUE IN THE
GEOLOGICAL INVESTIGATION OF NAHANNI EARTHQUAKE AREA

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SUMMARY

Recently there have been several large earthquakes near the North Nahanni River in the northeast Cordillera, Northwest Territories, Canada on 5 October 1985 (Ms 6.6), 23 December 1985 (Ms 6.9) and 25 March 1988 (Ms 6.2). The earthquakes occurred within a small relatively undeformed plateau, the Mackenzie Plain, in the Foreland Fold Belt created along the northeastern Cordillera during the Columbia or Laramide Orogeny.

One of the problems in the detailed study of geological and tectonic setting of the epicentral region has been lack of comprehensive geological and geophysical data. In this study an attempt was made to use satellite images of the epicentral region to compliment other available information. Detailed investigation of the surface structural features of Landsat MSS image over the epicentral area indicates that there are several northeast trending structural features intersecting the major northwest trending structures approximately at the earthquake epicentral region. These northeast trending structural features have never been mapped previously. These new information warrants further focal plane solution and field confirmation. The preliminary results are very encouraging and this study proves that the remote sensing techniques can provide a very useful tool in the analysis of geological hazards in remote areas.

A CONTRIBUTION OF MICROWAVE REMOTE SENSING
FOR SOIL EROSION FORECASTING

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SUMMARY

Soil erosion processes have been studied extensively in that they occur widely on hillsides where there has been a great change in the landscape due to intensive human activities. However, many more efforts are needed to develop improved erosion prediction technology in supporting soil conservation practices.

If a physical representation of erosion processes is considered, a new contribution of remote sensing could be the measurements of soil moisture content and soil roughness by means of microwave sensors, in that such parameters are related with soil erodibility and can be used, as inputs, in soil erosion models.

Preliminary activities concerning the evaluation of microwave remote sensing contributions for estimating soil erosion is about to start in the frame of SIR-C Project.

This paper deals with such activities, which are being carried out for the Italian test-site (near Florence) involving both ground based microwave measurements and modelling of soil erosion processes to optimize the use of SAR and radiometric data.

A RADAR STUDY OF MALASPINA GLACIER, ALASKA, WITH
IMPLICATIONS FOR SAFER ICE TRANSPORTATION AND GLOBAL CHANGE STUDIES

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SUMMARY

A U.S. Geological Survey (USGS) study of Malaspina Glacier found that X-band (3.2 cm) airborne and L-band (23.5 cm) satellite radar images show large patterns of complex bright and dark radar backscatter on the surface of the glacier. These patterns, 0.5 to 10 km in length, resemble bedrock features present in nearby mountains, such as cirques and drainage networks. Further, inspection of these airborne (1976, 1980, and 1986) and Seasat satellite (1978) radar images and other data sets indicate that the patterns have been relatively stationary for 10 years. This finding is provocative since Malaspina Glacier ice-flow velocities of 300 m/year near the center and 5 km/year near the edge of the glacier have been measured from moraine movement. Because of the observed discrepancy between the moraine movement and the stationary patterns, an interdisciplinary team of scientists visited the glacier in September 1988 to investigate the characteristics of the glacier's surface corresponding to these backscatter patterns.

Investigators found that the patterns on the radar images generally correspond to the topographic highs and lows of the glacier's surface. The bright signatures are usually topographic highs characterized by extensive crevassing, while the dark signatures are topographic lows with few crevasses. Because the patterns appear to remain stationary while the ice moves across the patterns, the investigators hypothesize that the glacier's surface features are an expression of the subglacial bedrock morphology. These features are thought to be similar to standing waves in a flowing stream, propagating up from the subglacier terrain, resulting in extensional flow related to topographic highs and compressional flow related to topographic lows. Airborne and satellite radar detect the features because crevasses and large hummocks on topographic highs act as radar reflectors and backscatter a large portion of the signal, whereas water and snow in the smoother-surfaced topographic lows reduce the return signal. Ice-penetrating radar surveys are planned to aid in developing this concept.

These observations and hypotheses have important implications. Because crevassed and uncrevassed zones can be identified using radar data, safe landing sites and transportation routes can be mapped to facilitate geologic exploration and mapping. This technique was used successfully during the 1988 field trip to Malaspina Glacier. Further, if the surface topography of this glacier and some other ice sheets is an expression of subglacial morphology, then it may be possible to develop fluid dynamics model for estimating ice volume for global change studies. This model might use remotely sensed data to measure ice sheet area, flow velocities, wave amplitude, and other parameters needed to estimate volume. In addition, because Malaspina Glacier has the largest piedmont lobe in North America (2,680 square km²) and is similar in many ways to the continental ice sheets of the Pleistocene, the study of Malaspina may give us a

better understanding of the dynamics of lobate ice sheets and also may help us to unravel the course of events, both climatological and biological, that accompanied the growth and retreat of the Pleistocene ice sheets. This knowledge of the course of rapid climate change and its impacts is helpful in understanding and predicting current and future global change. Other mapping and global change applications of radar are also being investigated as part of this study.

SUBMARINE DEPOSITIONAL FEATURES OFF NORTHWESTERN QATAR
PENINSULA, DEPICTED FROM LANDSAT-TM IMAGERY

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SUMMARY

The study area, as a part of the mid-southern side of the Arabian Gulf, is characterized by shallow, almost clear water, lack of suspended sediments, and its bottom is generally of uniform lithology consisting essentially of carbonates. In the present work, recently acquired Landsat-5 Thematic Mapper imagery (Path 163/Row 42, dated February 6, 1987) has been processed and interpreted for geological investigation of significant submarine depositional features off NW Qatar Peninsula.

The studied imagery, at scales of 1:100,000 and 1:50,000 were digitally prepared using unfiltered TM bands 1, 2, & 3 (B, G, R) and filtered TM band 3 (B, G, R). The imagery data of TM bands 1, 2, & 3 were statistically analyzed and a linear contrast stretching was applied to maximize the informational content for water features enhancement. This band combination allowed the water to appear in natural color, highlighting the significant underwater features.

Photogeological interpretation of the produced imagery has led to identification and delineation of some sand banks, tidal bars of particular S- and V-Shapes, as well as coral/algal capping and fringing reefs. The latter are closely associated with bathymetric highs of structural origin. Some of these reefs are still alive, while others are dry, accordingly they appear in various tones. Furthermore, it has been possible to elucidate that the fringing reefs are better developed around the windward periphery, i.e. towards the NNW 'Shamal' wind.

This work demonstrates the practicability of deriving considerable geological information on submarine depositional features from the visual interpretation of properly processed Landsat-TM digital data. However, ancillary data and ground-truth information on climatic, oceanographic and other environmental conditions are essential before and after interpretation of satellite imagery to ensure that the resultant output is consistent and accurate.

HIERARCHY OF PLANETARY FRACTURE SYSTEMS - ECONOMIC UTILIZATION

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SUMMARY

The Earth's planetary fracture network is highly complex in nature and is comprised of several orders and sub-orders of fractures which constitute a clear and recognizable hierarchy. Although these fracture systems are complex, they are also systematic in their patterns and in their spatial relations to each other within the hierarchy. As a result, it is possible to define their several roles in the development of economic deposits through time and, to utilize this knowledge in the search for new deposits and further development of existing deposits.

The several orders of fractures vary greatly in scale ranging from global and continental lineaments at one end of the spectrum to the ubiquitous systematic joint on the other. The entire range of remote sensing techniques can be effectively applied to the mapping and analysis of the various hierarchical elements within the fracture network. Utilizing the various remote sensing mapping techniques appropriately can establish the role of elements of the fracture hierarchy in controlling the location and development of economic deposits through time. This understanding in turn leads to more effective integrated use of conventional and unconventional exploration techniques as well as existing data sources by focusing attention on specific prospective targets.

The hierarchial elements of the planetary fracture network are defined by example. Applications of appropriate remote sensing mapping techniques are discussed. The utilization of fracture mapping in economic prospecting is illustrated at several levels by example.

CLASSIFICATION OF LINEAR SURFACE FEATURES BASED ON
TEXTURE SEGMENTATION OF RADAR IMAGERY

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SUMMARY

Texture analysis is an important aspect in image analysis because texture is an important characteristic of imagery. Texture is a collection of pixels which have specific relationships, where each pixel shares a common property and is geometrically connected. An image is assumed to have several textures, of which the total number is unknown. The purpose of segmentation is to decide the regions over which the selected texture property is uniformly distributed. The goal is then to select a similarity threshold that will separate one texture from the others. In consequence, similar textures may be discriminated if the measurement window is sufficiently large. However, the disadvantage is that small regions may be completely ignored in the process.

Feature segmentation in this research is based on the statistic of the gray tones of the pixels. By using quite a large window in the segmentation, then "higher order" moments in statistical analysis can be applied. The features are extracted from the image by describing the shape of the distribution with the use of the mean, which is used to locate the distribution, the variance which measures the dispersion, the skewness which describes the asymmetry, and kurtosis which expresses the peakedness of the distribution. The spatial distribution and dependence among the gray tones in the area is evaluated using the co-occurrence measure. Co-occurrence is an estimation of the number of times a gray tone appears in a specific spatial relation, in which the spatial relation has both a directional and distance parameter. Based on these statistical analysis, initial specific categories of ground cover are consolidated and clustered, which can then be interpreted.

The overall aim of this research is to find an optimal texture segmentation for linear feature detection, which introduces only minimal error. The data used is from the Intera Technology Ltd. STAR-1 SAR system of the Brazeau Range area NW of Calgary, Alberta. It is expected that effective development of these techniques will have relevance to the mapping of linear features and surface structures, especially in tropical and arctic areas, with persistent cloud cover.

STUDIES OF ACTIVE VOLCANOES USING VISIBLE, NEAR
INFRARED AND THERMAL INFRARED DATA

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SUMMARY

The use of multispectral thermal infrared data to map the relative ages of lava flows in Hawaii has been demonstrated via the detection of changes in the surface mineralogy and physical state of the flows resulting from weathering processes. These processes cause physical breakdown of the glassy rinds, precipitation of silica rinds, filling of vesicles, and breakdown and oxidation of mafic minerals. Resulting emissivity differences were detectable using data from the Thermal Infrared Multispectral Scanner (TIMS).

For active flows, quantitative estimates of the kinetic temperature require analysis of data from additional wavelength regions. The peak of the blackbody spectral radiance curve for an active flow or lava lake with a kinetic temperature of 1150k is near 2.3 microns. For lower temperatures, the peak shifts towards longer wavelengths. Given adequate sensor responses, these temperatures can be determined using data from the visible and reflected infrared, as well as the thermal infrared.

Image data from TIMS and from a Thematic Mapper Simulator scanner (NS-001) were acquired over the active Pu'u O'o lava flows in Hawaii in 1988. The instruments were adjusted so that the high radiance from the incandescing lavas did not saturate the detectors. The data were calibrated using internal blackbody references or known-radiance lamps, to allow conversion of measured instrument signal to incoming radiance. Analysis of the data allowed mapping of the temperature distribution of both active flow break-outs and the associated lava tube system.

NS-001 data were acquired over the three lava lakes at the summit of Mt. Etna, Italy on five successive passes spaced 30 minutes apart. The data were co-registered, calibrated, and corrected for surface reflectance contributions to the radiance signal. Conversion to temperature and application of a two component mixing model allowed determination of the areal extent of fire-fountaining and cracking of the lake surface, exposing 1150k material. Changes in behavior of the lakes as a function of time were detectable, indicating that turnover of the surface was occurring at this time-scale.

This work was performed at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration.

PHOTOGEOLOGY AND PHOTOGEOMORPHOLOGY OF THE SINJAR
ANTICLINE, NORTHWESTERN IRAQ

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SUMMARY

Analysis of Black-and-White airphotography and Landsat MSS data of the Sinjar Anticline northwestern Iraq was used to evaluate the relative effectiveness of these products for geological and geomorphological mapping and to determine the mass movement susceptibility of different landforms.

The Sinjar structure is rather typical of folded regions in the Mesozoic Tertiary Alpine orogenic belt of northern Iraq, and analysis of this structure may serve as a predictive analogue for study of other areas of the country. A major premise of the current study was that landform assemblages and processes can be interpreted from conventional black-and-white (~1:50,000 scale aerial photography, augmented by Landsat MSS imagery (1:250,000 scale) so as to produce a geomorphological-geological map (1:100,000 scale) of sufficient accuracy as to preclude the need for extensive ground-truth (field) verification.

Landforms of the Sinjar area have developed in response to several geomorphic processes, chiefly fluvial and mass-wastage. The land surface divides into convexoconcave and convex-rectilinear assemblage, each bounded by slope discontinuities. The area is further subdivided into 14 erosional-depositional landform units, each represented in color on the geomorphological map, and individually illustrated local or special features are represented by line symbols. Stereomodel mapping at 1:50,000 scale of 13 local areas of former or incipient mass movement susceptibility of different landforms encompasses examples of most slope instability forms in the Sinjar anticline, and provide criteria and patterns for recognition of slope failure.

Comparison of the geomorphological map with preexisting geological maps of Sinjar suggests that very accurate geological mapping ensues directly from geomorphological analysis of ~1:50,000 scale black-and-white air photos.

ASSESSMENT OF MERGED REMOTE SENSING AND GEOPHYSICAL
TECHNIQUES USED IN GLACIATED PRECAMBRIAN BEDROCK,
WOOD, PORTAGE, AND MARATHON COUNTIES, WISCONSIN

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SUMMARY

This project was designed to predict significant groundwater sources within Precambrian crystalline bedrock for an area in central Wisconsin covered by up to 100m of Paleozoic sedimentary and Pleistocene glacial units. The identification of thoroughgoing zones (up to 10 km wide) from Landsat TM imagery at 1:250,000 scale. These zones are believed to result from a variety of bedrock structures, including shear zones, foliated units and fold structures, thought to be favorable groundwater hosts.

The zones were to be defined further by merging and analyzing available potential field geophysical data with Landsat imagery, as well as field checking for the presence and nature of geologic structures associated with the lineaments. Resistivity and ground radar surveys were attempted in order to better determine the scale of the zones. Finally, results of the study were to be correlated with known well production in order to build a quantified, iterative exploration model.

To date, Landsat TM imagery has been processed, enhanced and interpreted. However, it is difficult to interpret linear zones exhibiting high moisture content from three band (1G, 2R, 3B) color composite, ratio, or principle component images. Nevertheless, field studies of bedrock fractures and foliation clearly discriminate major differences in trends, lengths, and densities among rock units (e.g. granite gneiss-amphibolite) or between sheared and unsheared phases of the same unit (e.g. metavolcanics). The widths of structurally favorable zones having high infiltration potential are on the order of 1-2 km wide.

Of the potential field data available, only gravity provided complete coverage of the area. Unfortunately, survey station spacings were sufficiently large (1-1.5 km) so that interpretation results were meaningful only at the regional and not prospect scale. Additionally, ground radar surveys proved useless owing to the high component of clay minerals in either the glacial cover or

local bedrock paleosols. Resistivity measurements show promise in predicting zones of high water content in Precambrian bedrock, again from 1-2 km wide zones.

Analysis of data from over 2,000 wells in Precambrian bedrock from the 18,000 km² study area has confirmed the presence of relatively narrow (1-2 km) cells having high groundwater flow as well as recognition of effective groundwater infiltration between Precambrian bedrock and the overlying units, despite local paleosols in the former. The hydraulic potential of the area has been determined and the flow within the "cells" has been correlated with mapped geologic and structural units.

Owing to the scale of identified zones of high groundwater flow in bedrock, it is anticipated that other remote sensing data may be more appropriate for exploration, particularly near IR photographs or radar imagery. In addition, it will be necessary to further investigate the relationship between regional drainage patterns and bedrock structures in order to establish drainage controls in areas of limited (<20 m) glacial cover. If successful, automated methods for the detection of linear/planar features from digital elevation models may provide a fruitful approach for the identification of groundwater-rich zones in areas of glaciated Precambrian bedrock.

GLACIOLOGICAL STUDIES BY REMOTE SENSING OF TERRA NOVA BAY (ANTARCTICA)

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SUMMARY

Work reports the results of preliminary research on remote sensing applications in glaciological studies of Terra Nova Bay area (Victoria Land). Repeated satellite images and aerial photographs can be used to carry out the variations of margins of ice-shelves and glacier tongues and their flow-rate. We compiled two "False color" mosaics from four Spot multispectral images of 19 December 1988 and two Landsat MSS images of 28 November 1972. The mosaic images were transformed in map projections by ground control points took from U.S.G.S. topographic maps scale 1:250.000 and map of the area around Italian base, scale 1:25.000. Investigations were carried out on two ice shelves, Hells Gate and Nansen Ice Sheet, and on an ice tongue of Campbell Glacier. Hells Gate is a small area; the variations of margins, its iceberg discharge and its flow-rate were pointed out by comparing aerial photographs of U.S. Navy took in 1956-57 and 1985 and Spot Image of 1988. Calculations of flow-rate and changes of the margins of Nansen Ice Sheet and Campbell Glaciers were measured comparing U.S.G.S. topographic maps compiled from tricamera aerial photographs taken 1955-63 and Landsat images of 1972 and Spot Image of 1988. Digitally enhanced satellite images point out the deflation and accumulation snow areas and give an indication on the main direction of katabatic winds.

COASTLINE CHARTING & ITS APPLICATION BY CORRECTING
TIDAL STAGE IN SATELLITE IMAGE CHENGBEI, HUANGHE RIVER DELTA, CHINA

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SUMMARY

On the offshore Huanghe River delta, the coastline varies rapidly affected by both a large proportion of the deposits from Huanghe River and marine actions. And the slopes of the delta have extremely low angles. Due to the difference between the time of satellite image and the time of ebb tide and flood tide, the change of the immediate waterline from satellite image interpretation cannot display the substantial change of the coastline.

In terms of the tidal data in Chengbei, the immediate waterline was transformed to 0-depth line on theorized datum by correcting the tidal stage. A series of the maps of the 0-depth line was made which show the substantial change of the coastline at a scale of 1,200,000. By superimposing of these maps, several characteristics of the coastline change in Chengbei were found.

Chengbei was near the outlet of the former channel of Huanghe River. The primary effecton was from the Huanghe River sediments. The coastline change of this area accompany with the channel changing. The different characteristics appear before and after the channel changing. Similarly, the different characteristics appear inside and outside the outlet area of the former channel of Huanghe River.

NIGHT-TIME INFRARED THERMOGRAPHY OF LANDSAT TM ON MT. ETNA VOLCANO

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SUMMARY

Measurement of radiance at satellite level in Thermal Infrared band (8-12 μm) theoretically permit to compute the energy radiated from the target and then the surface temperature, obtained from a mean value of energy over pixel's surface. Because temperature is not homogeneous over the surface, the resulting temperature must be considered as apparent one.

By using Thematic Mapper radiometer of Landsat IV and V, thermal anomalies will be described with a resolution of 120 m x 120 m. The studied scene was acquired on 23 October 1986 at 10 p.m. Radiometrically and geometrically corrected TM 6 data show clearly that isoradiance curves follow the contour lines of the digital model of topography. This adiabatic gradient, i.e. the air temperature decrease due to its adiabatic release, was statistically computed over four distinctive zones (NE, NW, SE, SW) of Mount Etna to take in account two effects: the wind on the NW slope remarkable on raw data, and the thermal inertia on South slopes. We have also computed the vegetation index on a daytime Landsat scene of June 1984, over the same area. Superposition of both scenes leads us to mask on the thermal one the zones with high index and so to compute precisely the real adiabatic gradient corresponding to the bare soils (lavas and pyroclastics).

Corrected data show a large thermal anomaly corresponding clearly to the summit craters and to their influence areas (200 to 300 meters wide).

Moreover, several hot anomalies stand out:

- i) in the North of the Voragine crater, several pixels which correspond to a cooling lava flow dating of September, so one month before the scene acquisition.
- ii) on the flanks of the Valle del Bove, anomalies attributed to a cliff effect.
- iii) in the center of the Valle del Bove, an interesting linear and radial feature, linked to the South-East crater.

INTEGRATION OF REMOTE SENSING AND GIS FOR A
HYDROGEOLOGICAL ASSESSMENT OF THE BRIDGETOWN AREA, NOVA SCOTIA

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SUMMARY

A pilot study area was selected to create a hydrogeological database integrating information acquired from Landsat Thematic Mapper imagery with conventional data stored in a Geographic Information System. The study area is located in a segment of the Annapolis Valley, Nova Scotia, encompassing the town of Bridgetown. An expanded industrial park is proposed in the vicinity of Bridgetown; therefore, investigation of potential environmental impacts associated with this facility and its water resource requirements are essential.

The following are among the main objectives of this investigation:

- 1) To understand the relationships between topographic and geomorphic landforms with surface and groundwater regimes.
- 2) To detect drainage patterns, geologic lineaments, rock types and to investigate their relationships to recharge and discharge areas.
- 3) To assess land use/land cover characteristics of the area to indicate their utilities for groundwater recharge.
- 4) To prepare a hydrogeological map demonstrating the areal extent of principal aquifers and their productivity.

The following procedure is used:

- 1) Image enhancements using the micro-based PCI-Easi/PACE and mini-based Dipix-Aries digital image processing systems.
- 2) Integration of conventional data, such as:
 - a) Bedrock and surficial geology maps,
 - b) Soils coverage maps,
 - c) Aquifer localities and depths obtained from well data,
 - d) Topographic contour maps, and
 - e) Climatology data, into the database.
- 3) Utilization of the ESRI-ARC/INFO Geographic Information System to store the data and understand the interrelationships between various data sources, and to create a multi-disciplinary database useful for hydrogeological investigation and modelling.
- 4) Interpretation of the database to meet the above mentioned objectives.

Relationships between surface and groundwater regimes could be better understood by considering:

- 1) Information acquired from the integration of land use/land cover, surficial geology, geomorphology, and hydrology.
- 2) The spectral and textural information gained from satellite generated data.

It is expected that the establishment of a hydrogeological database could provide useful management information for communities which are experiencing industrial expansions. Environmental impact assessments and management of water resources are of increasing importance to expanding urban areas and could be investigated using an integrated RS/GIS approach similar to the database created for the Bridgetown area.

At present this investigation is progressing and the completion date is set for late July, 1989.

LANDSLIDE RISK ASSESSMENT USING REMOTE SENSING AND OTHER GEO-DATA SETS

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SUMMARY

Landslide activity is related to a number of geo-environmental parameters, such as, lithology, land-use, distance from major tectonic features, local structure, topography and slope azimuth. The paper deals with the development of a method for landslide hazard zoning, using multi-data sets in a Geographic Information System (GIS) approach and taking data from Ramganga Catchment, Himalayas, as an example.

Remote sensing data consisting of aerial photographs and repetitive Landsat coverages were used to generate data on landslide distribution, land-use, geology, and structure. The interpretations were controlled by field and published data.

Based on data of 522 landslide occurrences, statistical relationships of landslide activity with various geo-environmental factors such as lithology, land-use, slope aspect, distance from major tectonic zones have been evaluated.

For collective interpretation, an empirical approach has been used wherein statistical relationships of the geo-environmental factors with the landslide occurrences are converted into a risk factor (called LNRF, defined later) given on an ordinal scale. The landslide nominal risk factor (LNRF) is considered here as:

$$\text{LNRF} = \frac{\text{Landslide incidence (area per unit area) in a particular geo-environmental subcategory}}{\text{Average landslide incidence in the various subcategories of that parameter}}$$

The LNRF ratio values have been broadly grouped into three (i) LNRF < 0.67 (low risk), (ii) 0.67 < LNRF < 1.33 (medium risk) and (iii) 1.33 < LNRF (high risk). Weights of 0, 1, and 2 have been ascribed to the above three LNRF categories respectively. The entire catchment area was grided into unit cells. Separate overlays were prepared for each of the geo-environmental parameter. In each overlay, unit cells were ascribed certain weight factors from amongst 0, 1, 2 depending upon the LNRF value. The values for each grid cell in the overlays, were summed.

In this summation, lower values imply more stable slopes and higher values imply more unstable slopes. The entire study area has been grouped into three categories: (i) high risk of landslide, (ii) moderate risk of landslide, and (iii) low risk of landslide.

The work furnishes an interesting example of integrating remote sensing data with other geo-data sets for applied engineering-geologic investigations.

AUTOMATIC EXPLORATION ACCESSIBILITY ANALYSIS USING LANDSAT-TM DATA

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SUMMARY

The Environmental Research Institute of Michigan (ERIM) has developed an algorithm that recognizes road networks, railway lines and river courses in a satellite image data set that has been geometrically corrected to a specified map projection. As the lines of communication are identified in the image data, their locations are recorded in the annotation overlay of the data set. After adding geographic tick marks and digital annotation to the overlay it is used to generate an accessibility map of a frontier exploration area or prospect site where accurate, up-to-date maps are not available. The algorithm utilizes both the radiometric and spatial information in the image data set to locate the lines of communication.

For this case study the algorithm is applied to a portion of a Landsat TM image data set to show the procedure involved in automatically generating an accessibility map using only the TM and satellite ephemeris data. The map is then analyzed for trafficability and logistical support in the region for future exploration activities -- access to port facilities, access for geologic field parties, location of seismic lines and possible drill pad locations. The accessibility map overlay can be added to a GIS data base covering the study area for use with other geological or geographic data overlays.

The final map in this study was compared to existing topo maps of the area to determine accuracy and completeness.

FLUORESCENCE OF METAL-STRESSED SPRUCE NEEDLES
AND ITS IMPLICATIONS FOR GEOBOTANICAL REMOTE SENSING

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SUMMARY

Since the launch of Landsat in 1972, reflectance data collected in the visible to shortwave infrared region have been employed in oil and mineral exploration to detect changes in the spectral characteristics of vegetation caused by toxic concentrations of gas or heavy metals in the underlying soil. Both single and multiple band combinations and transformations have been used in the detection process with varying degrees of success, in part, because of the broad bandwidths and low radiometric sensitivity of the sensor systems. In addition, the vegetation features being measured are, with the exception of canopy chlorophyll and water content, primarily of a biophysical nature (canopy structure and biomass) and therefore are a non-specific indicator of stress. As non-stressed related changes in canopy biomass also result in changes in canopy biochemical constituents, the spectral reflectance characteristics of both features are not consistently accurate measurements of canopy stress. This can give rise to false or missed geobotanical anomalies - both costly mistakes in an exploration programme.

Although stress in vegetation is often manifested by some form of morphological change in a plant canopy, biochemical changes offer a more reliable measure of stress. The photosynthetic efficiency of a plant is related to the concentration and vitality of the chlorophyll pigments in its leaves or needles, which, in turn, controls the level of chlorophyll fluorescence exhibited by a plant. A decrease in leaf chlorophyll content results in the impairment of the photosynthetic process and a subsequent increase in leaf fluorescence. Plant fluorescence can therefore be used as a direct measure of its health and vigor and as an indicator of stress. As only the green leaves of a plant are photosynthetically active, other plant and background components, such as the branches and trunks of trees, do not contribute to the thereby contaminate the fluorescence signal, as is the case with reflectance measurements.

Experiments with the fluorescence of coniferous needles excited with laser-induced light have identified several chlorophyll fluorescence bands in the 400-800 nanometre region that give a direct measure of the chlorophyll-a content and photosynthetic efficiency of the needles. The magnitude of these emission bands are related to the vitality of the trees and, by association, the canopy as a whole. Needles collected from a Norway spruce forest overlying a copper-lead-zinc deposit display changes in the fluorescence bands that correspond with the heavy metal concentrations in the underlying soil and, by inference, the degree of metal stress experienced by the trees. Chlorophyll measurements from the same trees show a similar relationship with the soil metal content. The implications of these results for the use of fluorescence measurements in a mineral exploration programme will be discussed in the context of present and future sensor systems.

THIRTY YEARS TEACHING REMOTE SENSING TO
GEOLOGISTS, ENGINEERS, AND ENVIRONMENTALISTS

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SUMMARY

Each year for the past 30, I have given one to three university-sponsored, week-long courses to scientists and engineers. Over 3000 participants have attended them. The course is focused on instructor-guided interpretation of a manual containing 680 high quality B&W airphoto stereograms of varying scales. The stereograms have been selected from about 4000 client-requested remote sensing projects. In addition, 300 slides showing Landsat, radar, thermal IR, colour IR and conventional B&W airphoto imagery, and related ground scenes, are viewed and interpreted with continuous verbal question-and-answer input from class participants. Emphasis is given to exploration and engineering geology, natural hazard mapping, environmental geology, hydrogeology, and soil and bedrock mapping and evaluation for multidisciplinary projects.

Course participants attending usually have some prior background knowledge in remote sensing. One hundred short-answer questions on diagnostic feature recognition and multidisciplinary application are given at the beginning and end of the course. Results of these quizzes normally show less than 10% correct answers before course commencement, increasing to over 80% at the end of the 35 hour-long course. Over the years, these multidisciplinary courses have ranged in size from 25 to 60 participants, with an average attendance of about 40.

Examples presented deal with petroleum and mining exploration, engineering geomorphology, detecting gravel and groundwater supplies, engineering site and route selection, and related environmental studies. Examples are chosen to demonstrate techniques, methodologies, data integration and related field work, and problem definition and solution.

**QUANTITATIVE COLOR EVALUATION AND DISCRIMINATION OF GEOLOGIC MATERIALS
USING TRANSFORMED REFLECTANCE - A CASE STUDY**

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SUMMARY

Color is an important diagnostic parameter for identification of a feature. Here a relationship between color and spectral reflectance is developed and used as an advantageous tool for discrimination, especially, of earth materials using remote sensing.

There are several methods available for quantifying color, notably the RGB and the Munsell systems. While the former enables synthesis of any color as a combination of the primaries, the latter is closer to the perception of color as seen by the human eye. This paper describes the development of a technique for the use of these systems for discrimination of geological materials.

The technique developed is designated as the optimal rotational transformation technique. It seeks a transformed value of multi-band spectral reflectance using optimisation involving nonlinear rotation of axes in the multi-dimensional signal space. The optimisation is carried out with respect to transformed reflectance and the quantified color. As a result, linear mathematical models are obtained between color components and transformed reflectance for both color systems mentioned above.

Application of these to a predominantly basaltic area on the western coast of India gave promising results. The study used digital data of colors and Landsat and laboratory radiometric values for the area. The prediction of Hue of the materials and their use in discrimination between them was possible with an exceptionally high degree of accuracy. A slight reduction in accuracy was noticed in poorly graded granular materials. In general, prediction of value and Chroma was prone to greater scatter, although, for discrimination, the difference was found to be sufficient and accurate.

The study demonstrates that this technique provides a useful input for better digital classification for geological interpretation.

APPLICATIONS OF SATELLITE GEOLOGIC MAPPING
IN HUMID TROPIC ENVIRONMENT OF EAST JAVA

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SUMMARY

The satellite Landsat colour composite 1:250,000 scale MSS imagery was used for a range of thematical mapping as a part of integrated watershed management and development planning study of the Brantas Watershed (1.6 million ha) in East Java, Indonesia.

A geologic map was prepared using an existing old reconnaissance geology map and rapid field checking. The satellite imagery provided significant improvements in updating of geologic boundaries and identification of new previously undetected formations.

The geologic formations identified on the satellite imagery define major physical characteristics of the study area, especially terrain, soils, hydrology, and land use.

The geologic map provided a major input in compilation of terrain classification, soil type, present land use, drainage, multidiscipline land suitability, and agro-climatic zonation maps.

In addition, a close relationship was established between specific rock types and erodibility of appropriate surficial geologic and soil materials. A qualitative ranking of major geologic formations according to the relative erodability index was carried out for the major rock formations of the East Java. Subsequently, this data was used for identification of erosion hazard and assessment of suitability of soil conservation treatment to major soil types. Areas with very high erosion hazard and shallow soils were closely associated with specific geologic formations.

As a result of application of the Landsat imagery in geologic mapping, some substantial additions were carried out on existing geologic maps, specifically, locations of major volcanic flows, delineation of karstic limestone, alluvial, alluvio-marine, and marine deposits.

The application of the recent Landsat satellite imagery in geologic mapping resulted not only in identification of new previously unrecorded data, but also allowed to integrate the basic geologic data into series of thematical maps used for regional and national land use planning.

Low price and easy availability of the Landsat imagery also contributed to the increased effectiveness, efficiency, time, and money saving if compared with the conventional mapping techniques based on utilisation of up to date, high level aerial photography.

THE APPLICATION OF SATELLITE REMOTE SENSING
TO AGGREGATE EXPLORATION IN ALBERTA

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SUMMARY

The scarcity of aggregate is becoming a significant obstacle to economical construction of roads and other facilities in many parts of Alberta. Early research on applying remote sensing to aggregate exploration in this province has produced inconclusive results, and a call for a more thorough investigation. A comprehensive study, therefore, was undertaken by Gorecki and Schmidt to determine the usefulness of digitally processed Landsat TM imagery for locating sand and gravel deposits in Alberta.

This study was based on principals of geobotany. A study area was selected where there existed evidence for unique vegetation complexes and moisture stress being associated with near surface aggregate. One Landsat TM quadrant was acquired for this area, located in west central Alberta.

Image processing began with unsupervised classification which was performed in order to identify dominant forest themes. These themes were then used to generate principal component statistics, and a color composite of the three most significant principal components was produced.

This was followed by supervised classification, with essential data on training sites being supplied by Alberta Transportation and Utilities. This information helped identify 5 training area types, where these were classified in terms of forest cover, overburden thickness, and aggregate deposit thickness. Signature generation and maximum likelihood classification were performed based on both raw data (all TM Bands), and principal components. Spatial filtering was also applied to the data, in order to determine whether surface lineaments show any correlation with recognized aggregate trends.

Evaluation of results shows a high percentage of test sites (known aggregate deposits that were not used for training) being picked-up as "aggregate themes" by the supervised classifications. In addition, some aggregate themes showed a strong relationship with geomorphic features which have been mapped by others as coarse-grained in nature (e.g. beach ridges and various fluvial deposits). These features were more visible on imagery enhanced by means of spatial filtering. The unsupervised classification and enhanced composite imagery were not as useful for narrowing-down aggregate prospects, but tended to support the results provided by supervised classification. It was concluded that digitally processed Landsat TM data can be an effective "front-end" exploration tool in parts of Alberta covered by natural forest vegetation.

UTILIZING MULTISENSOR AND GEO-DATA
FOR ANALYSIS OF NEOTECTONICS IN SW NORWAY

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SUMMARY

The bedrocks of the Sunnhordland area of southwestern Norway are criss-crossed by fracture systems of different deformation styles and orientations. Of particular significance are lineaments with NNW-SSE and NE-SW trends. Furthermore, it is well documented that late Paleozoic-Mesozoic dyke-filled fracture systems are of great importance to the structuring of the area, and that older structural elements are characterized by reactivation.

The area includes Precambrian migmatites and NE-SW trending phyllitic rocks of the Cambrian-Ordovician deformed during the Caledonian orogeny. The Precambrian basement is exposed in the south and north of the study area.

The region as a whole offers a unique potential to integrate geophysical, geological, and remote sensing data for a comprehensive study of neotectonic activities and their interaction with reactivation of fault zones.

The ongoing study employs a "multidata approach" from microscopic to synoptic scale as it utilizes field observations, thin sections, satellite, and aerial photo derived geological data, seismicity data.

Satellite data used to map lineaments in the region were acquired by Landsat-TM and the panchromatic mode of SPOT. Availability of multisensor data allowed to undertake a multiscale

approach to the study. Regional structural features were mapped on the enhanced Landsat-TM image while the SPOT-panchromatic image was used to obtain more detailed structural information. The lineament study as conducted on two bases: statistical evaluation of lineament parameters to extract areas of significant geo-structural zoning and feature by feature correlation of lineaments and known faults in the area.

Lineament characteristics such as vegetation and superficial deposit covers, bedrock, and lineament intersection localities were extracted analyzing each band individually, and finally the most informative bands were combined as "false color composites". Key areas spotted on the Landsat-TM image were subsequently used as a baseline to carry out more detailed structural mapping on the SPOT subscenes. All the images used in the study were digitally enhanced with interactive processing and enhancement algorithms in a ContextVision GOP-300 image processing system. The final geological remote sensing step to be applied is an aerial photography interpretation of the selected field localities.

Seismicity data recorded during a recent earthquake and a preliminary follow-up field study indicated that the earthquake epicenter is located on a NW-SE trending lineament which is identified in the Landsat-TM and SPOT-panchromatic scenes.

This lineament has also be recognized as a fault zone by previous workers, and levelling surveys across faults confirm recent vertical displacements. This is also indicated by shore line displacement in the area.

The seismic event falls into a pattern of recent earthquakes in outmost Norway and the adjacent continental shelf. The preliminary results indicate that both post-glacial rebound and regional tectonic stress contributes to the present crustal strain in the area.

A REMOTE SENSING BASED GEOBOTANICAL INVESTIGATION OF
ULTRAMAFIC ROCKS ALONG A REGIONAL FAULT ZONE

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SUMMARY

Ultramafic rocks are useful as indicators of tectonic environment and commonly have associated Ni-Cu sulfide and/or platinum group element (PGE) mineralization. We have investigated geobotanical relationships associated with the detection of ultramafic bodies with Landsat Thematic Mapper data.

This study was carried out in the Superior Province of NW Ontario. The region is in the southern boreal forest and has a continuous vegetation cover. The region has a thin to discontinuous till cover. Geologically, the region is characterized by a series of alternating granite-greenstone and metasedimentary lithostratigraphic belts. A series of mafic-ultramafic bodies are distributed along the Quetico fault zone, an east-west trending feature, which parallels the boundary between two of the regional lithostratigraphic belts. Knowledge of the distribution of the mafic-ultramafic bodies, as provided by remote sensing, may provide constraints on concurrent work being conducted by one of us (E.L.M.) on the structural interpretation of the Quetico fault.

In this study, we have examined rock-soil-vegetation spectral relationships associated with an ultramafic intrusion in the vicinity of Chief Peter Lake. The Chief Peter intrusion is approximately 2500 ft by 1500 ft. It is a chemically zoned body with a hornblendite (less mafic) rim surrounding a peridotitic, more mineralized core. Bulk rock chemical analysis has revealed concentrations of up to 2500 ppm Cr, and 430 ppm Ni. Many of the Quetico fault zone mafic-ultramafic bodies, including the Chief Peter intrusion, have been investigated by Canadian exploration companies for platinum group element potential.

Analyses of soil samples overlying the Chief Peter intrusion indicate that soil geochemistry is being influenced by the ultramafic bedrock. We examined the spatial variation in soil chemistry over the intrusion by trend surface and cluster analyses. Soils were collected over a 2³ rotatable factorial design: X₁ and X₂ were approximately coincident with longitude and latitude respectively with a 50 m unit spacing; X₃ was soil depth with a 30 cm unit spacing. Major and minor elements Al₂O₃, Fe₂O₃, MgO, CaO, FeO, MnO, TiO₂, Na₂O, and K₂O were normalized to SiO₂; minor and trace elements B, Ba, Cr, Cu, Nb, Ni, Rb, S, Sr, Y were normalized to Zr. Trace elements were selected for their known importance as nutrients and/or potential for indicating ultramafic bedrock below.

Both multivariate analyses point to a very immature soil with compositional variation being controlled by the configuration of the ultramafic intrusion. Major elements cluster in associations that are typical of rock compositions, e.g., mafic vs. felsic clusters. Spatially, the major and minor elements are strongly linearly related to X_2 , weakly related to X_1 , and are independent of depth. Trace elements are more depth dependent but, with several exceptions, cluster with those major elements with which they normally occur in crystalline rocks.

Detection of the Chief Peter ultramafic with August TM data is based on vegetation species assemblage changes which have been found to be associated with lithologic changes in this region (Bell, unpublished data). These species assemblage changes are lost in areas of disturbed vegetation. Preliminary analyses of spectral data indicate that it is possible, however, to mask out areas of disturbed vegetation. Further analysis has shown that there is an approximately 20% difference in mean NIR reflectance associated with vegetation over the Chief Peter ultramafic body relative to that on surrounding metasedimentary rocks. Thus, the potential exists to detect ultramafic bodies in areas of undisturbed vegetation with geobotanical remote sensing.

A BACKGROUND GEOBOTANICAL MODEL FOR EXPLORATION
IN THE CARAJÁS MINERAL PROVINCE, BRAZIL

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SUMMARY

Orbital RS (optical spectrum) has been successful in geologic exploration in arid and semi-arid environments. For tropical rain forests regions, however, results are rare and rely on spatial/context rather than on spectral attributes. A Background Geobotany approach was developed for geologic exploration in cool and temperate regions based on the hypothesis that the nature and distributions of plant communities occur as a result of environmental conditions on which at different levels, geology (lithology/structure) represents important control. The concept focus on community level and has been tested through digital image processing of orbital RS (TM-Landsat/SPOT) and DEM data.

In Brazil, the Carajás Province in the Amazonic craton constitutes the most important mineral province in the country. Different geologic situations coupled with tropical weathering have created conditions for a presence of wide range of mineral deposits such as Fe, Al, Mn, Cu-Pb-Zn, Ni, Cr, W and Sn. The Province is characterized by rugged topography, thick latosol profiles and almost absence of bedrock outcrop. The vegetation is typical of tropical rain forest with a complex canopy and a great variety of species. This region, therefore, presents an ideal opportunity to evaluate RS technologies in one of the most unfavourable conditions for lithological discrimination.

The investigation has focused on physical/environmental controls on vegetation more than the chemical attributes of the substratum and is an adaptation of the Background Geobotany approach for this particular kind of environment. A 230 square km test site was selected, centered on the Pajuca 4E Cu-Zn deposit. The area is part of the northern border of the Carajás Mountain and is characterized by three main geologic terrains: (1) medium to high grade metamorphic archean rocks known as Xingu Complex constitutes the embasement; (2) a well oriented archean volcanosedimentary sequence named as Pojuca Group, mainly greenschist to amphibolite facies rocks with several Cu and Cu-Zn deposits and (3) an early proterozoic low

grade clastic sediments called Rio Fresco Group. The analysis was developed on two sets of data: six reflexive TM-Landsat bands and DEM images of elevation, slope and aspect. The methodology was divided in three components: RS, DEM, and 3D (perspective). The data set was analysed independently through a combination of enhancement (frequency equalization, simple and complex band - ratios and principal component transformations) and unsupervised classification (clustering) techniques. A feature selection routine Optimum Index Factor, was used to select the best bands for color composites with TM data. The integration with DEM products was done on a qualitative mode and through 3D enhancement based on perspective transformations using the best color composite enhancement and values of elevation.

The preliminary results of the investigation have shown that 11 RS biophysical classes were detected, the majority with spatial correlations with previous geological units. In addition, elevation and slope have presented an important role in the definition of the biophysical classes and in the characterization of the geobotanical background patterns. For an economic standpoint, the detection of a spectral pattern associated with the Pojuca Group opens perspectives in the future use of the methodology to delineate its occurrence elsewhere in the Carajás Province outside the area of detailed mapping.

THE ASSOCIATION OF SPECTRAL RESPONSE AND METALS CONCENTRATION
IN SAGEBRUSH ON HYDROCARBON AREAS

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SUMMARY

Previous research shows that the concentration of iron and manganese in sagebrush leaves varies in association with the vertical migration of hydrocarbons. This phenomenon is related to the effects of a reducing environment on the availability of metals to plants. Other lines of research show that certain metals in plant leaves cause a change in the spectral response of the leaf, and may be indicative of ore bodies. Present research examines the variations in spectral response of sagebrush, and the associated concentrations of iron and manganese in the leaves. The results of this work can move bio-geochemical exploration for hydrocarbons from a heavy dependence on field work to a greater reliance on remote sensing techniques using high spectral resolution scanners such as AVIRIS.

Spectra were collected in field sites where sagebrush samples and earlier been collected for analysis of iron and manganese concentration from three locations in Nevada. In each of the field studies there was a definite pattern to the Mn/Fe ratio suggesting microseepages of hydrocarbons. Spectra of growing vegetation in the field and dried leaves in the lab were obtained. Preliminary results indicate that leaf spectra vary in response to the concentration of iron and manganese, or perhaps other metals not identified, in sagebrush leaves. Further work will be needed to determine the limits and validity of these observations. If these experiments prove valid, there will be a major new role for high spectral resolution remote sensing in exploration for hydrocarbons.

ADAPTATION OF THE BACKGROUND GEOBOTANICAL APPROACH FOR REGIONAL SCALE
MINERAL EXPLORATION UTILIZING GIS TECHNOLOGY, BAIE VERTE, NEWFOUNDLAND

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SUMMARY

Research activities in geobotany are active in the remote sensing community due to the necessity to understand geobotanical relationships in order to extract geological information from remote sensing data in many Canadian environments. Many of these research activities are site specific, the methods being developed in small detailed areas. This paper reports on preliminary results of a project whose objectives are: 1) to transfer background geobotanical methodologies to a regional scale exploration program, and 2) to develop methodologies for the integration of geologic data sets within the framework of a geographic information system (GIS).

The Baie Verte peninsula of Newfoundland, Canada, was chosen for study because of current exploration interest for base and precious metals. Gold mineralization is found in both massive sulfide deposits and epigenetic vein deposits. Much of the mineralization is associated with shear and/or fault zones, and is located in several host lithologies including Ordovician ophiolitic suites, mafic and felsic lavas and (possible) late PreCambrian granites. This presents several favourable opportunities for the introduction of remotely sensed data within the exploration program.

The methodology which was developed utilized PC-based image analysis and GIS software for analysis, integration, and modelling of the data. Landsat TM, SPOT panchromatic, C-band airborne SAR, geochemical and geophysical digital data were used in the study. Digital integration in the GIS environment required preprocessing of the different data in order to integrate normalized data sets.

Geobotanical (definable geologic relationships) and biophysical (non-definable geologic relationships) classes were identified. Lineaments corresponding to structural features as well as lithologic contacts were interpreted and extracted readily from the imagery. The other datasets provided additional and supporting information to the remote sensing data in isolating favourable conditions for mineralization. The geologic information which was derived from the remote sensing data as well as the other supporting data has contributed actively to the exploration for both gold and massive sulfides in the study area.

PHOTOGRAMMETRIC APPLICATIONS IN EXPLORATION & MINING GEOLOGY

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SUMMARY

Photogrammetric data capture; using aerial and terrestrial photography, Landsat, or SPOT Imagery has improved dramatically in recent years. Analytical photogrammetric plotters are capable of data acquisition to an accuracy of 1.4 microns, used in conjunction with low cost computers, can analyze and present data in a multitude of ways for the geologist. Photogrammetry is a powerful planning and monitoring tool in exploration and mining programs. As a result, ground survey methods of acquiring topographic and cultural data for exploration and mining planning, are gradually being phased out and are replaced by photogrammetric acquisition methods. Survey data is used only for control purposes. Photogrammetric data so acquired can be used and manipulated by the geologist, engineer, to obtain the most informative and least expensive product for the project. The product provided may be in the form of DTM data file on magnetic tape, hard or soft copies of maps, cross sections, volume computations, three dimensional models, orthophoto images, and stereomates. The advent of this powerful new technology makes it important that the photogrammetrist and the user mutually understand the advanced and problems in each other's field of expertise.

TECTONIC FRAMEWORK, DEFORMATION ZONES, AND GOLD MINERALIZATION IN THE
RED LAKE PORTION OF THE UCHI SUBPROVINCE, WESTERN ONTARIO
- AN INTEGRATED LANDSAT STUDY

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SUMMARY

Linear elements corresponding to fault or shear zones in Landsat MSS imagery of arid or semi-arid terrains have an analogous counterpart in the forested, till-mantled regions of the Superior Province of the Canadian Shield even under conditions of minimal bedrock exposure. Preliminary evidence suggests that differential compaction of clayey tills over ridged bedrock induces subtle edaphic and hydrological differences in the overburden which are, in turn, replicated by small but detectable variations in the boreal forest cover. These linear geobotanical features apparently track structural elements in bedrock with a high degree of reliability.

A Landsat MSS reconnaissance study of a 15,000 km² portion of the Uchi Subprovince centered on the Red Lake "greenstone belt" revealed a lineament array which can be resolved into four principal directions. Preliminary field data indicates that these directions correspond with penetrative or semi-penetrative shear fabrics. Deformation zones appear to be delineated by clustering or bundling of lineaments belonging to a specific group and the morphology of this clustering is thought to be a rough indication of the brittle-ductile strain regime. Relative age relationships (from oldest to youngest) of the various lineament directions are: east-west, northeast-southwest, northwest-southeast, and north-south. All lineament systems cut impartially across the Archean supracrustal rocks of the greenstone belt, including indwelling felsic intrusive stocks and the surrounding granite-gneiss terrain alike so that all, at least in their present form, must be at the earliest very late Archean in age.

Most of the major gold deposits at Red Lake occur along a dominant east-west striking deformation zone so that the overall tectonic setting of the gold mineralization is broadly comparable to the important gold-producing districts of the Abitibi Subprovince which are closely associated with the Porcupine-Destor and Kirkland-Larder Lake "breaks". The only real difference at Red Lake seems to be the obscuring of this ancestral structure by repeated tectonic overprinting.

Landsat-derived lineament arrays have proven to be compatible and complementary on regional to local scales with computer-enhanced geophysical data. Merging of lineament directions with total field, calculated vertical gradient and aeromagnetic shadow maps is a useful operational procedure in gold exploration. Evidence is accumulating that at least some of the gold deposits are controlled by highly specific structural features at the confluence of two or more distinct deformation zone trends.

AN INTEGRATED APPROACH TO GEOBOTANY: PRELIMINARY RESULTS FROM THE
INTEGRATION OF MODELLED VEGETATION SPECTRAL DERIVED FROM MEIS DATA WITH
DIGITAL MAP DATA, MICHIWAKENDA LAKE, ONTARIO

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SUMMARY

Analysis of airborne multi-detector-electro-optical imaging scanner (MEIS) data was conducted over a mineralized till site near Michiwakenda Lake, Ontario, Canada. The bedrock geology of the area consists of a mafic to felsic metavolcanic suite together with ultramafic and minor intrusive felsic rocks, intruded by diabase dikes. Geochemical sampling of the bedrock and concurrent overburden in the area indicates varying degrees of mineralization for Cu, Zn, Fe, and Ni. The objective of the study was to determine if the vegetation growing on the base metal mineralized sites is spectrally different from background sites and whether this can be quantified through analysis of the airborne multispectral data.

The MEIS data was acquired in September 1986, just prior to leaf senescence, and consists of eight bands centered at wavelengths 480, 548, 675, 698, 710, 734, 746, and 776 nm. The scanner was flown at an altitude of 15,000' to produce imagery with a spatial resolution of 3.2 m. The scanner was fitted with a curved filter set, which removed the passband blue-shift problem inherent in pre-1986 flat filter data.

Preliminary processing of the imagery involved radiometric calibration of the imagery and the conversion of the digital signal for each band to "reflectance" values between 0 to 255 by normalizing to the extraterrestrial spectral irradiance.

Bulk processing of the imagery concentrated on the use of an inverted Gaussian model to characterize the red edge region of the vegetation reflectance curve between 680 and 800 nm.

Using this model, four parameters: the red edge shoulder height, the calculated reflectance minimum, the calculated reflectance minimum wavelength, and the Gaussian deviation were calculated on a pixel-by-pixel basis for the entire image set and output to separate image database files.

Subsequent analysis of the imagery is based upon an integration of the stress parameter files with digital maps databases consisting of: 1) tree species distribution, 2) soil geochemistry, and 3) topography. These were used to identify spectral anomalies related to base metal mineralizations.

GEOBOTANICAL MAPPING OF A METAL-STRESSED FOREST WITH THE
FLI AIRBORNE IMAGING SPECTROMETER

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SUMMARY

The use of remote sensing data in the search of ore deposits has involved both low spatial, spectral, and radiometric resolution sensor systems, as employed by the Landsat MSS, Thematic Mapper, and SPOT satellites, and somewhat higher resolution airborne systems, such as the Bendix Daedalus multispectral scanners. In the last five years, the development of airborne imaging spectrometers has made it possible to acquire reflectance data at far greater spatial, spectral, and radiometric resolutions, thereby permitting more exact information to be obtained on the reflectance characteristics of surface features and increasing the accuracy of their identification and analysis. For geobotanical applications, the ability to employ precise spectral bands for the measurement of specific plant biochemical and biophysical constituents (e.g., chlorophyll-a) may result in a more accurate detection of plant physiological changes related to metal stress from buried orebodies.

The Fluorescence Line Imager (FLI) airborne imaging spectrometer developed by Moniteq Ltd. of Canada records spectral data in 288 contiguous bands over the wavelength interval 430-805 nanometres and digitized at 12 bits. Two data collection modes are available: a full spectral (288 bands), but reduced spatial mode configuration, and a full spatial, but reduced spectral (8 bands) mode configuration. For the full spatial mode arrangement, pixel dimensions of less than 5 metres along track and 0.5 metres across track are obtainable.

FLI data in both modes were acquired over a metal-stressed Norway spruce forest growing in soils containing high concentrations of copper, lead, and zinc associated with an underlying polymetallic base metal deposit. Reflectance information was extracted from both acquisition mode data sets and spectral curves generated from stressed and non-stressed forest areas. The wavelength positions of the chlorophyll-a absorption maximum at approximately 680 nm and the red-edge inflection point were derived, using an inverted Gaussian reflectance model developed at York University in Toronto, plus the intensity values at 680 nm and in the near-infrared plateau region at about 780 nm. Changes in these values were related to soil metal concentrations and canopy chlorophyll and leaf area indices (LAI) obtained from the test site, in an effort to determine the suitability of using the FLI spectral values for heavy metal stress detection in coniferous forests.

GEOBOTANICAL APPLICATIONS OF NIGHTTIME
THERMAL INFRARED AVHRR DATA IN SCANDINAVIA

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SUMMARY

The prospects of using remote sensing of the emitted infrared energy from the Earth's surface for studies of surface thermal properties have been the subject of research for more than 20 years. However, this technique has been applied mainly in semi-arid and arid climatic areas where rock surfaces are bare. The application of remote sensing in geological studies faces difficulties when a study area is masked by the vegetation. Sometimes the masking effects of vegetation become so severe that well-established conventional methods of geological mapping cannot be applied directly. In these difficult circumstances the only answer to this masking problem of vegetation is to find out the relationship between vegetation and bedrock geology. Sometimes it is difficult to identify the spectral differences of the same type of vegetation growing over different rock types. However, differences in the water content in the same type of vegetation on different rock types may reflect contrast in the temperature of the vegetation. Recent green house experiments have demonstrated that the temperature contrast between vegetation of different water content is enhanced in the nighttime. Therefore if the areas masked by vegetation are to be studied for geological mapping thermal infrared images of nighttime data should lead to improved discrimination between two different rock types based on differences in the temperatures of vegetation, whereas daytime images of these areas are unable to improve discrimination between two different rock types. The thermal infrared images can, of course, be acquired at any time of the day or night. However satellite remote sensing faces a problem in acquiring information from the land surface in regions where clouds are frequent. The frequent passes of NOAA series satellite provide opportunities to acquire cloud-free and snow-free data.

In this paper, the application of nighttime thermal infrared AVHRR data in geological mapping using geobotanical techniques is discussed. Discrimination of various rocks and identification of linear features have been possible in nighttime thermal infrared AVHRR data of Scandinavia. The main aims of the present study are (a) to explore the potential application of nighttime AVHRR data for geological mapping, (b) to determine the best time of year for gathering data for this type of study when vegetation on different rocks will show contrasting characteristics, (c) to determine the best image-processing techniques for nighttime geobotanical studies, and finally (d) to establish the usefulness of composites of day and nighttime digital data from thermal infrared channels to improve geobotanical mapping methods.

APPLICATIONS OF MEIS DATA TO GEOBOTANICAL MINERAL EXPLORATION
STUDIES IN NE ONTARIO, CANADA

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SUMMARY

The overall aim has been to develop an interdisciplinary approach to geobotany involving geology, biology, and remote sensing with the major objective of determining the relationships between metal-induced stress in vegetation and spectral reflectance. Two sites in northeastern Ontario, Canada, were studied; the first, near Gowganda, where silver and cobalt-nickel arsenide mineralization is exposed on the surface, and the second, in Kelvin Township, 35 km to the west, where base metal anomalies have been reported in the overburden.

Bedrock mapping along with sampling a A and B horizon soils and a variety of vascular and non-vascular plants have been carried out. The amounts of various elements (Fe, Mn, Cu, Ni, Co and As at Gowganda and Cu, Ni, Co, Pb, Zn, Mn, Ca, Mg, and Cr at Kelvin) in the vegetation and soils were determined using atomic absorption spectrophotometry. In addition, at the Kelvin Township site six stands of essentially pure Trembling Aspen (*Populus tremuloides*) trees were sampled for leaves, twigs, trunk wood, and roots. The six aspen stands were located on colour infrared airphotos and precisely delineated on a surveyed 10 m grid. Base metal concentrations in soils from two of the six stands indicate that they are anomalous, whereas the remainder are not. The relationships between soil metal levels and those in various parts of the plants proved to be complex with no systematic pattern for all the elements studied.

Airborne MEIS multispectral digital imagery was acquired for the Kelvin Township site at a spatial resolution of 1.06 m, in five 0.01 μm spectral bands, centered at 0.680, 0.713, 0.753, 0.782, and 0.792 μm . The ground-based information was used to develop a supervised classification of the MEIS imagery, using a PCI micro-based image processing system. The results demonstrated the ability of the classification to identify anomalous reflectance from the aspen trees located over the base metal soil anomalies.

EFFECTS OF DROUGHT ON LITHOLOGIC MAPPING USING GEOBOTANICAL REMOTE SENSING

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SUMMARY

The Serpent Mound Cryptoexplosion Structure is located at the junction of Highland, Pike, and Adams counties in southwestern Ohio. The relationship of lithology and forest communities is well established in this area. The feasibility of using Landsat TM and geobotany to produce lithologic maps has also been demonstrated. This area is an excellent choice for a project of this nature. Subscenes of Landsat TM data of this area were acquired for August 16, 1987 and August 18, 1988.

Two methods of analysis were used to determine if the effects of the drought could be detected with Landsat TM. Three color composite images were created using bands 2, 5, and an ratio of 5/4 in the blue, green, and red planes respectively for both data sets. In addition, analysis of spectral indices in n-space were used to detect the amount of green biomass present in the image. Difference images of both methods for the 1987 and 1988 data sets were produced. The different images may be used to determine the changes in the amount of green biomass from 1987 to 1988.

Lithologic maps were also produced by performing supervised classifications of both the 1987 and 1988 data sets. A difference image was produced to see what extent drought affected lithologic mapping.

PROSPECTING BASED ON GEOBOTANY AND REMOTE SENSING

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SUMMARY

In Canada, prospecting for minerals is often difficult as much of the bedrock is blanketed by sediments that were eroded and transported over large distances by continental glaciers. Exploration is further complicated by the presence of vegetation which covers a major part of the country. To help resolve the problems encountered in prospecting in glaciated terrain, an integrated approach based on remote sensing and principles of drift prospecting, geobotany, and biogeochemistry as tested in three different sites in Canada.

In glaciated terrain, the bedrock is eroded by flowing glaciers, and debris are incorporated in the glacial till and spread out over large areas. Localized mineralized bedrock can therefore be the source of large soil geochemical anomalies. Prospecting methods involving the study of vegetation are based on the principle that plants have to draw their nutrients from elements present in the soil and should therefore reflect the chemical composition of the soil around them. Soil geochemical anomalies can influence plant chemistry (including chlorophyll production), distribution of species and health conditions. Analysis of spectral signatures, particularly in the infrared region, makes it possible to identify various types of vegetation and to study their distribution. It also permits to identify certain stress conditions related to geochemical anomalies. In this study, remote sensing is used to identify both geobotanical and biogeochemical anomalies.

The approach was applied to three different geological settings to evaluate its use in mineral prospecting: an ultrabasic geochemical anomaly located in southeast Quebec, gold mineralization in Star Lake area, and uranium anomalies in Wollaston Lake area in central and northeast Saskatchewan.

The study in southeast Quebec is now completed and has shown that the high concentrations of ultrabasic debris in the glacial till affects the distribution of tree species and also causes vegetation stress such as a decrease in chlorophyll production, late leaf development in the spring and early senescence in the fall. The remote sensing study confirmed the results obtained by the geobotanical and biogeochemical investigations and analysis of multitemporal imagery was able to precisely identify the geochemical anomaly.

The remote sensing study (using multitemporal data from Thematic Mapper) in Star Lake area was not able to identify any geochemical anomaly, as these are relatively small and the mineralization associated with gold occurrences (quartz filled fractures) are not toxic to plants. The multitemporal imagery was, however, able to differentiate between bedrock types by monitoring spring vegetation flush.

Research is still underway in the Wollaston Lake area, and preliminary results of multitemporal Landsat imagery shows that uranium anomalies can be detected by remote sensing.

ANALYSIS OF GREEN VEGETATION DETECTION LIMITS IN 1988 AVIRIS DATA

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SUMMARY

The Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) is an experimental sensor built by NASA at the Jet Propulsion Laboratory. With 224 bands having approximately 10 nanometer bandwidths, the instrument has been designed to permit the analysis of fine spectral features known to occur in rocks, soils, and vegetation. The exploration utility of spectral data having fine spectral resolution has been clearly demonstrated (e.g. discrimination of clay minerals and chlorophyll red edge shifts). However, because of the limited coverages afforded in the AVIRIS program to date, there is a dearth of studies coupling field measurements and an analysis of AVIRIS data.

The present study focuses on determining what level of green vegetation cover is required to produce a recognizable signal in 1988 AVIRIS data. We are using an AVIRIS flight line covering the eastern flank of the Santa Cruz Mountains near Stanford, California acquired on August 31, 1988. On this flight line we have located a series of five commercially operated Monterey Pine plots of uniform density. The trees are planted in rows and have been cultivated to remove the vegetation between trees. The variation in soil texture and color between plots is minimal. The plots are thus mixtures of green vegetation and bare soil. The percent green vegetation cover in the five plots was measured three weeks after the AVIRIS overflight. The plots range in percent cover from 2% to over 50%. The AVIRIS pixels of the five plots were extracted from both raw and radiometrically corrected AVIRIS data. The radiometrically corrected AVIRIS data has been converted to units of reflectance using a series of calibration targets.

We will present and discuss: 1) the AVIRIS spectra (raw, radiometrically corrected, and reflectance) of the five Monterey Pine plots, 2) the correlation between AVIRIS vegetation index values and percent green vegetation cover, 3) a detailed examination of the chlorophyll red edge in the data, 4) an evaluation of which vegetation spectral features are most important in measuring trace quantities of green vegetation in imaging spectroscopy data, and 5) a comparison of data quality in 1987 and 1988 AVIRIS data. Results indicate a close correspondence between AVIRIS vegetation index values and green vegetation cover.

REMOTE DETECTION OF TREELINE:
A POSSIBLE METHOD FOR MEASURING ENVIRONMENTAL STRESS

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SUMMARY

In light of current concern about the effects of acid precipitation and other pollutants on the northern spruce-fir forest, investigation into the use of remotely sensed satellite data to monitor change or stress in the forest environment is of particular interest. Forest stress is manifested in many ways, some of which can be detected with remotely sensed data, others of which can not. This study focuses on an indicator of stress that should be both sensitive to environmental change and easily detected: the position of treeline. Treeline is the elevation on a mountain where the natural environmental stress of severe weather conditions is so great that it inhibits continuous forest growth.

The hypothesis of the study is that an increase in environmental stress (natural or anthropogenic) to a forest will have the most effect on those trees which are already under stress, in particular those at treeline. Die back of treeline trees would lower treeline. If the hypothesis holds, it will be very important to have baseline information on treeline location and to follow changes in it; remote sensing data may be an effective source of this information.

The field site chosen for this study is the Presidential Range of New Hampshire, which includes New England's highest mountain, Mt. Washington (1961 m). Landsat Thematic Mapper data collected on 10 June 1984, 5 July 1987, and 9 September 1988 were used.

The major surface types near treeline are forest, scrub (krummholz), grass, and exposed rock. Between 2 and 5 training sites for each surface type were chosen. Band ratios were used to minimize the effects of terrain shadowing while preserving spectral differences among surface types. Two dimensional scatter plots were analyzed for all TM Band pairs. Both TM 5/4 and TM 7/4 ratios are effective in maximizing the image contrast between forest (dark) and exposed rock (light). In both of these ratios, grass falls between forest and rock though closer to rock while scrub falls close to forest. The TM 3/1 ratio improves the separation of grass from the other surface types while scrub, which is made up of low trees, merges both spectrally and spatially with forest. The three dimensional ratio space of TM 7/4, TM 5/4, and TM 3/1 best separates the forest, scrub, grass, and exposed rock surface types. Hue is another way of representing the spectral information contained in the band ratios; treeline is clearly distinguished on hue images as well as ratio images.

The results of the analysis of TM data agree well with a published map based on extensive field work and large scale air photointerpretation, and indicate that this method may be an effective way to monitor changes in treeline over time.

GEOBOTANICAL INVESTIGATIONS LEADS TO BETTER SEISMIC DATA IN
REMOTE SENSING OF THE GABUN-PARACALE MINING PROJECT

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SUMMARY

In the coming decades of the 20th century version of modernized Geobotanical investigations will play major roles for mineral explorations, as we have been undertaking in our mining areas with the present usage of remote sensing vertical technological processes. Presently, valuable correlativity is attained in relational of Indicator Flora or the generalized studies of the plant species as related to mineral deposition in the Gabun-Paracale Mining Project. In the Iron staining of major mining claims of our mining areas there has been major breakthroughs in remote sensing by photointerpretation of the Satellite Photographs by Geobotanical Investigations as used in flight data or aerotriangulatory techniques in aeromagnetic surveys, we have detected that there has been major focus of plant species like cashew forest growth in the nearby iron ores mineral depositional area of the Gabun-Paracale Mining Project. More so, there has been greater "dwarfism" of major tree stocks in our heavily foliated or forested areas. So, our major knowledge of Geobotanical Investigations as relational to our ground truth data have resulted in pinpointing major drill holes and lineamentals that lead to greater geostructural and heavy faulting in anticlinal mountainous or digital terrain models (DTM). In making valuable thorough geobotanical Investigations of the Gabun-Paracale Mining Project, we have resulted in accessing the extent and exact drilling operations of our drilling crew. Thus, it has resulted to efficiency in our "mines" management operational behaviors and has check our mines safety engineering standards and operations.

GEOBOTANICAL LITHOLOGIC MAPPING IN ONTARIO:
REMOTE SENSING APPROACHES AND CAVEATS

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SUMMARY

Remote sensing in vegetated terrains has been the focus of an increasing number of geologic endeavors, if not by choice, then by virtue of the fact that two-thirds of the earth's land surface is vegetated. Where soils have developed as strong functions of parent material, such remote sensing geobotanical investigations can be conducted, albeit with difficulty. In areas that have been glaciated, however, even this tenuous foundation in geobiological reality is not absolute. Nonetheless, increasing evidence suggests that geobotanical relationships can be successfully exploited in glaciated terrains as long as multidisciplinary approach is undertaken that makes cautious use of all available ancillary data, including field data. The present work discusses geobotanical lithological mapping investigations conducted in several locations in the southern boreal forest in areas of thin, discontinuous glacial and continuous vegetation cover. The work was designed to investigate geobotanical information rather than as an outcrop location technique. The focus is on results from NW Ontario, near the Quetico fault system.

Assuming a region is naturally vegetated, remote sensing is often complimentary to geobotany. Considering the rather industrious nature of man, if such undisturbed vegetation exists, the area is often remote and relatively inaccessible. Canada, is, thus, an area where remote sensing and geobotany can be complimentary.

During several years of exploration and lithologic mapping in Canada by one of us (VS), it was consistently observed that there was a higher proportion of coniferous cover over metavolcanics and a higher proportion of deciduous cover over metasediments. We have now quantified this relationship and extended the work to include granites, migmatites, and ultramafic bodies thus covering the major rock types in the NW Ontario shield area. Differences in tree size and spacing between the lithologies as well as different species assemblages were

documented from field studies. Preliminary analysis of TM data suggests that there are spectral differences associated with these assemblage differences and that such differences appear to be a function of tree size, crown shape, spacing and thus canopy top physiognomy as spectral information on image inertia values were important to lithologic discrimination.

In addition, and more importantly for geological exploration purposes, a species assemblage pattern associated with ultramafics was found at five different locations. Ultramafic bodies are aligned along subprovince boundaries in the area. Such rocks offer clues to tectonic history and setting and can also be associated with economic mineralization. Through understanding species distributions, the remote sensing imagery can be interpreted to obtain lithologic information that could yield information on mineral exploration. Details of field and remote sensing technique and results are presented.

ON THE INTERCORRELATION BETWEEN MULTISPECTRAL
CHARACTERISTICS OF NATURAL OBJECTS

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SUMMARY

The results of analysis of radiation characteristics of water basins: gulfs, salt lakes, river lots, seashores, and soils covered by different types of vegetation-winter wheat, maize, oats, sugarbeet, etc. on infrared, visible, and microwaves are presented in this report. The equipment, used in the experiments, including microwave radiometers on wavelength 2.25, 18, and 30 cm, nonscanned type of infrared radiometer in waverange 2 - 20 mcm, infrared scanner AGA-THP-I, multichannel spectrometer "Barness" in waverange 0.4 - 12 mcm, is described. The results of calculations of some statistic characteristics of signals in noted frequencies, are given.

It is shown that autocorrelation function along with absolute values of radiation in noted waveranges permits to identify different nature objects and to obtain quantitative values of their characteristics. For example it is possible to distinguish different types of water basins by using a ratio between microwave and optical signals correlation radii. The availability of correlation between radiation characteristics of some lots of earth and water surface on microwave, infrared, and visible waveranges is shown, too. The stability of this correlation depends on geophysical parameter variations: temperature, mineralisation, and chemical pollution values of water subjects, soil moisture, type and vegetation stage on agriculture fields. Empiric formulas, that characterized the correlation between radio brightness temperature on microwaves and brightness coefficient on waveband 0.76 - 0.9 micrometers for soil lots, covered with vegetation. Some applied problems of joint different remote sensing data processing are discussed. In particular, the principles of taking into account measuring data from devices, placed on different carriers are described. The algorithm, that realized this task, is presented. The methodic basis of joint application of different remote sensing data for evaluation of water basin mineral resources, of their physical-chemical parameters, for evaluation of vegetated terrain characteristics, in particular, joint application of non-scanned microwave and panorama IR-data for mapping of soil moisture, optimum wavelength choice for evaluation of nature formations conditions. Some results of water basin and soil coverings remote sensing data joint processing are presented too.

AN INTERACTIVE, PC-BASED, MAP-ORIENTED INDEXING
SYSTEM FOR REMOTE SENSING DATA

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SUMMARY

Chevron Overseas Petroleum's remote sensing data (including multispectral satellite and radar images and tapes, aerial photographs and mosaics, and maps) are being indexed into an interactive GIS system that is map-oriented and resides on a networked Apple Macintosh SE personal computer. This system is possible because of recent advances in computer technology. It integrates diverse data into a simple graphical format that is easily understood and accessed by explorationists, increasing utilization of our in-house resources.

Prior indexing systems were difficult to maintain, access, and update. These included hand-drawn map indices dating to the 1950's and digital tabular lists begun and terminated at various times during the early 1970's and mid 1980's.

With the present PC-based system, data retrieval is quick and easy. Initially the user points to the area of interest from a map of the world. This selection (as with all interactions) is done with a mouse. Maps of increasing scale are opened as the user "zooms-in" on the area of interest. When at the desired level (country for this database), the user selects the data of interest (satellite images, airborne photos, radar, small scale regional mosaics, etc.) from a graphical menu. If satellite images are selected, the country is overlain with general outlines of SPOT, MSS, and TM coverage. By selecting TM coverage, the program will overlay the country with a detailed World Reference System (WRS) map (Landsat 4,5 path/row centerpoints) and individual scene footprints. Shaded footprints indicate scenes in Chevron's inventory. By pointing to a shaded scene, information is displayed adjacent to the map listing path/row, date of acquisition, cloud cover, Lat/Long, type and location of in-house products, etc. The user can print the list and map by pushing a button on the screen. Moving to another shaded footprint continues the interrogation. During data entry, the outlines of satellite/airborne coverage and Path/Row - K/J maps are created by hand with a digitizing tablet or by scanning.

Using the system is self-explanatory and requires no special knowledge beyond geography and familiarity with a Macintosh computer. The hardware and software are common within our office environment. An Apple Macintosh SE, a dot matrix and laser printer, and a digitizing tablet form the basic hardware while MacTablet, SuperPaint, Hypercard and MapMaker comprise the basic software. The system is networked over telephone lines, increasing interactive accessibility. Data can also be transferred to diskettes and mailed to other offices to assist in their search for in-house data. An overhead projector can be utilized with the computer to interactively query the database during conference meetings.

This system can be expanded to include most geographically oriented data. It can easily index data from new sensors and it can handle large collections. Most importantly, this interactive, map-oriented system has proven to be simple, reliable, accessible, and cost-effective.

We propose to present this as an interactive "live" event by using a liquid crystal screen that fits over a standard viewgraph. This screen would be hooked up to a Macintosh SE that contains our data base. Audience participation would be encouraged.

C-3

STRUCTURAL INTERPRETATIONS OF THE AJJAJ SHEAR ZONE OF SAUDI ARABIA
AND WADI GHADIR AREA OF THE CENTRAL EASTERN DESERT OF EGYPT
UTILIZING LANDSAT THEMATIC MAPPER DATA

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SUMMARY

The Arabian shield has undergone considerable rearrangement due to deformation by the Najd transcurrent fault system since its accretion (600 to 900 ma). The Najd is the largest known Proterozoic fault system with a NW-SE strike length of 2000 km across the Arabian shield and transcurrent displacements of up to 200 km. This study utilizes the spectral information of TM data to make structural interpretations within the Ajaj segment of the Najd shear zone of Saudi Arabia, and within the Wadi Ghadir area of the Central Eastern Desert (CED) of Egypt where structures were possibly associated to the Najd event. A linear mixing model was used to produce images of lithologic endmembers which allow delineation of folds, ductile shear zones and brittle faults. Our interpretation map suggests that the Ajaj Shear Zone (ASZ) was dominated by ductile deformation which resulted in a minimal sinistral displacement of 25-30 km. Our map shows regional variations in the width and orientation of the ASZ. The eastern segment of the ASZ is oriented east-west and appears to be dominated by strike-slip ductile displacement. In contrast its western extension is oriented north-northwest and should lead to an increased thrust component. The Wadi Ghadir area of the CED of Egypt represent the logical target area to search for the continuation of the ASZ in the Nubian shield. The Wadi Ghadir area contains part of an ophiolitic melange widespread in the CED. The complexity of this terrain has precluded detailed field mapping. Our study of the TM data for this area has revealed the presence of discrete east-west and north-northwest oriented sinistral shear zones identified from the rotation of lithologic layering, rotation of dykes, and reduction of block size within the melange. This confirms a possible connection between this area and the Ajaj shear zone prior to the Red Sea rifting.

LITHOTECTONIC DOMAIN IDENTIFICATION BY STATISTICAL ANALYSIS OF
VISUALLY AND COMPUTER-EXTRACTED LINEAMENTS: A CASE STUDY
FROM THE CAPE SMITH BELT NEW QUEBEC

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SUMMARY

Lineaments observed on remotely sensed images can represent boundaries between very localized spatial areas of traceable 'discontinuities', often recognizable by the distinct gradients across them. Identification of lineaments are often made visually (manually) but can also be obtained automatically using image processing techniques. This paper introduces an algorithm for the extraction of lineaments consisting of edge detection, edge selection, edge-linking, and heuristic line-linking. While the subjectivity of the manual method may filter out noise and lineaments nonsignificant to the particular study, the computer method is both faster and relatively accurate. In this study, comparisons of both of these methods is presented from a LANDSAT-TM image of the western part of the Cape Smith Belt.

The Cape Smith Belt is a Lower Proterozoic, predominantly volcanic, tectonic belt preserved as an East trending synformal trough across the Ungava Peninsula, northern Quebec. Belt parallel lithological units are structurally stacked and display good lateral continuity. to the south, Proterozoic cover rocks overlie, in fault contact, a basement of older Archean terrain.

Field investigations of this area indicate that each lineament domain delineates mappable lithotectonic groups. Statistically significant orientations of lineaments in each of the four domains are both structurally and lithologically controlled. Their characteristics are summarized below:

(1) Watts Domain: Rocks in this domain are metamorphosed up to amphibolite facies and are poorly represented in the scene. Locally, a single set of short (2-5 km) curvilinear lineaments appear to reflect the well developed schistosity or gneissic layering in the metavolcanic and metasedimentary units.

(2) Chukotat Domain: This lithotectonic domain is almost entirely composed of extrusive basalts and consanguineous intrusive sills at greenschist facies. A prominent belt parallel lineament master set spaced 1.5 - 5 km apart are interpreted to be thrust-faults. Less prominent, but closer spaced (250 - 1000 m apart) subparallel ones are consistent with the orientation of volcanic layering. An orthogonal, or in places conjugate, pair of very short (0.5 - 2 km) rectilinear lineaments are intimately associated with the fault related lineaments. These brittle features correspond to measured orientations of well developed joints in the basalt.

(3) Povungnituk Domain: Lithologically heterogeneous, this domain consists of interlayered metavolcanics and metasedimentary units. Intrusive mafic sills remain as an important component of this group. Numerous long and closely spaced (0.5 - 1.5 km) parallel linear and curved lineaments outline lithological contacts between faulted and folded stratigraphy.

(4) Archean Domain: Generally, the basement lineaments are rectilinear and 1 - 3 km in length, forming an orthogonal set in the South of the scene. A weakly defined subcircular structure may reflect pre- or syntectonic plutonic body. This is supported by the spatial occurrence of a magnetic susceptibility anomaly seen on aeromagnetic maps. The peneplaned granodiorite and granitic lithologies expresses surficial glacial features well.

A NEW CONCEPT OF DIGITAL PROCESSING OF MULTISPECTRAL
REMOTE SENSING DATA FOR GEOLOGICAL APPLICATIONS

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SUMMARY

The increasing amount of multispectral information of earth's surface in quite different portions of the electromagnetic spectrum improved the integration possibilities in geological investigations significantly. Presently, data of the Landsat Thematic Mapper (TM) are the most striking tool for geological applications which is mainly caused by TM bands 4 and 7.

A most effective use of the manifold spectral informations, however, requires also new strategies in combining the different spectral bands. Until now, the combination of TM bands 1, 4, and 7 via the B-G-R-approach has been designated as a kind of 'standard product' for geological mapping especially in arid to semi-arid areas.

By this presentation, we want to demonstrate, that a concept which is basing on the physical information content of the data available and the general spectral behavior of the phenomena which have been monitored creates improved products not only for non-vegetated but also in intensive vegetated areas. Contrary to the principle component analysis where the weighting factors exclusively are basing on the statistics of the given data, our concept allow a pre-definition of them. By this, specific phenomena on the ground and contents of the tasks in mind can be enhanced more flexible. The color presentation of the result is realized via the I-H-S-approach which, in addition, gives increased possibilities for the consideration of other image processing products (e.g. 'achromatic component' of TM bands 1, 2, and 3) and enables a more unique interpretation.

The concept will be demonstrated on the basis of TM data from Southern Bavaria and SPOT data of the Djebel Amour/Algeria.

ADAPTIVE FILTERING ON MULTIPLE-BAND IMAGES USING THE HIS TRANSFORM

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SUMMARY

Spatial filtering techniques are widely used in remotely sensed imagery to bring out lineaments and to obtain various degrees of edge enhancement for geological applications.

In most natural environments spatial filters yield good results. However, when the image characteristics vary widely on scales smaller than the filter size, undesirable effects are introduced, such as "ringing" near edges. We have implemented an adaptive filtering technique to overcome these problems. The technique is based on "tracking" local image characteristics and adapting the filter accordingly.

Multispectral images may be filtered either band by band or by transforming the data, filtering just one band of the transformed data, then inverse transforming the result. This paper compares these techniques, using the hue-intensity-saturation transform as an example of the transform approach, and explores their value for geological applications.

COLOUR ENHANCEMENT AND SHADOW SUPPRESSION TECHNIQUE FOR TM IMAGES - IMAGE PROCESSING FOR LITHOLOGY AND ALTERATION IDENTIFICATION IN S-E SPAIN

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SUMMARY

Colourful and shadow free images are generally preferable for geological interpretation and mapping of lithology. A comprehensive method for producing high quality shadow-free colour images is introduced in this paper, illustrated by an example of geological application in S-E Spain.

The method comprises three techniques, used in separate states:

Step 1: Band Selection Many techniques have been developed to improve colour display by statistical band selection and band decorrelation. The principle of these techniques is that three bands with low inter-band correlations tend to produce a high quality colour composite. Based on this principle, a technique for selecting three band combinations for colour composites has been developed. This technique gives high rank only to those 3-band combinations with low correlations between every two bands of the three. An alternative method using spectrally adjacent band combinations also produces good quality images for lithological interpretation.

Step 2: Balance Contrast Enhancement Technique (BCET) Based on three bands with very low inter-band correlations, a poor colour composite may still be produced if the average brightnesses of individual bands are significantly different from each other. In this case, there is colour bias in the composite. A simple and effective contrast enhancement technique, BCET, was designed to solve this problem. The BCET can stretch/compress an image (band) to a given minimum, maximum, and mean without changing the basic shape of the histogram of the image and therefore three balanced bands with exactly the same value range and equal average brightness can be produced for colour composition. Experimental processing shows that even three bands with quite high correlation can still produce a high quality colour composite after BCET enhancement.

Step 3: Shadow Suppression Ratioing is a traditional way to suppress shadows. However, ratios cannot remove shadow effects completely. A new approach based on colour transformation is used to produce a special colour image from 7 TM bands. Theoretically, the colours in this image represent the 7-band spectral signatures of different ground objects. As the band

reflectances of a ground object are not sensitive to the variation of illumination, shadow effects are suppressed very effectively. Vegetation can also be subdued by certain band combinations with appropriate colour transformation.

A sub-scene of a TM image of S-E Spain was processed by this method. A very colourful and shadow-free image was produced. The image is excellent for lithology interpretation. The major rock types as well as superficial deposits in the area are clearly shown in different colours on the image, especially the altered lithologies with close relation to gold mineralization (post Aplines volcanics). Areas with kaolinization and montmorillonite are distinguished from each other and from similar lithologies (such as limestone), and superficial deposits. Lineaments along lithological boundaries are also well displayed. A major lineament in NW direction not shown in existing geological maps is revealed in the enhanced image.

SELECTION OF LANDSAT TM BAND AND BAND-RATIO COMBINATIONS
TO MAXIMIZE LITHOLOGIC INFORMATION IN COLOR COMPOSITE DISPLAYS

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SUMMARY

Optimal depiction of geologic information in a trichromatic color composite image relies upon the selection of three channels (e.g., bands or band ratios) that are individually informative and collectively minimally redundant. Because the reflectance bands of Landsat Thematic Mapper (TM) provide 20 possible band combination and 455 possible ratio combinations, a statistical procedure for guiding the choice of combinations is highly desirable.

Several methods of statistical channel selection based on the separability of classes have been proposed, but their computational requirements are prohibitive (if fully implemented) and they require substantial a priori knowledge of scene content. In conflict with this, (1) the construction of color composite displays typically occurs before much is known about a scene, and (2) the analyst may be interested in all spectral variability and not just that which occurs between defined classes. Consequently, general-purpose channel selection is arguably best guided by methods that do not rely upon the definition of classes.

Previous class-independent selection procedures have used channel variance and channel correlation as measures of image information and redundancy, respectively. However, channel variance is completely irrelevant as an indicator of image information in a noise-free system and is virtually irrelevant in the selection of Landsat TM channels. Thus, selection is more reasonably based only on channel correlation and subjective considerations of image noise. Using these criteria, studies using both laboratory spectra and Landsat TM data revealed the following conclusions.

For geologic studies, the dominant factor controlling the selection of Landsat TM bands for inclusion in a color composite image (barring vegetative and atmospheric considerations) is the prominence of hydroxyl-bearing minerals in the scene. Hydroxyl-bearing minerals primarily include clays, micas, amphiboles, serpentine, and epidote-group minerals (but also include miscellaneous silicate, sulfate, copper, and other minerals). TM band combinations that include both band 5 and band 7 (especially 1,5,7) provide the best discrimination of lithologic materials if hydroxyl-bearing minerals are important in a scene, whereas bands 1,4,7 provide are best if hydroxyl-bearing minerals are neither prominent nor of specific concern to the interpreter. The four combinations that exclude bands 5 and 7, such as 1,2,3 ("natural color") and 2,3,4 (standard color infrared), consistently rank lowest for lithologic discriminability.

For band ratios, essentially all reasonable groupings of minerals are best discriminated by a combination of ratios that include one ratio of the short-wavelength bands (3/1, 4/1, or 4/2), the

ratio of the long-wavelength bands (5/7), and a ratio of one band each from the short- and long-wavelength band groups (e.g., 5/4 or 5/3). Practical experience is consistent with this in that the ratios 3/1, 5/4, and 5/7 in blue, green, and red, respectively, have been found to be very effective for the discrimination of lithologic materials.

APPLICATION OF REMOTE SENSING IN THE FIELD OF DESERTIFICATION
INVESTIGATIONS - AN EXAMPLE BY USE OF DATA OF A TEST SITE
IN THE SAHELIAN ZONE OF MALI

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SUMMARY

The most crucial environmental problem in the Sahelian Zone is the increase of desertification. Desertification is the impoverishment of terrestrial ecosystems under the impact of man. It is the process of deterioration in these ecosystems that can be measured by reduced productivity of desirable plants, undesirable alterations in the biomass and the diversity of the micro and macro fauna and flora, accelerated soil deterioration and increased hazards for human occupancy.

In the course of the last decade, remote sensing has proven its high potential for earth observation and became a powerful tool in quite different fields of application, in particular in the field of land cover mapping. Of course remote sensing can not solve the problem of desertification, but is best suited for the monitoring of relevant phenomena, which is important for further steps of desertification control and for planning of actions to reclaim affected land. Some important aspects of the capabilities of remote sensing data will be demonstrated by a test site in Mali in the region around Gire, west of Sokolo and the Canal du Sahel.

The most effective integration of remote sensing requires a well defined strategy, which fundamentally has to take into consideration the capabilities of operationally available remote sensing data and adapted digital image processing techniques.

Our presentation is focussed on a comparison and valuation of the Landsat-MSS and -TM data and the Japanese MOS-01 data. On the basis of so-called standard products (false colour composites) it will be demonstrated that, for purposes of mapping on medium scales, the most crucial points are the spectral capabilities of the different sensors. It can be stated, that a successful elaboration of relevant surface phenomena (e.g. land cover) requires the consideration of information given by the short-wave-infrared; in particular, the combination of the TM bands 1, 4, and 7 in a special approach is best suited for the solution of the tasks in mind. The requirement for an increasing ground resolution, however, is of secondary importance. In a further part of our presentation, we will demonstrate a concept of digital processing of Landsat-TM data for differentiation of soils and vegetation versus soil adapted to the specific conditions of the selected area. The procedure starts from the interpretation of reflectance profiles, which enables the definition of the most significant bands and/or band combinations (e.g. ratio). Basing on these results, most suitable colour combinations for visual interpretation will be presented.

MICRO TULIPS (MICROCOMPUTER BASED TERRAIN UNDERSTANDING AND
LAND INFORMATION PROCESSING SYSTEM)

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SUMMARY

Digital image processing methods are widely used for extracting terrain cover information from remotely sensed data. Due to recent advancements in microcomputer technology, microcomputer-based systems became more popular as image analysis tools. Processing speeds of microcomputers are comparable to those of mini computers of previous ages, and the storage capacity of disks now exceed 500 MB.

Most of image analysis techniques available on these systems still process remotely sensed data on a pixel by pixel basis. On the other hand, human interpreters analyze images through an object-oriented approach, using higher level of understanding about ground cover classes. This type of processing is to achieve very difficult with conventional sequential computers.

In CCRS, a project named "microTULIPS" is being conducted to develop an integrated system for remote-sensing-based terrain understanding.

The system provides various object-oriented information extraction methods with stronger user interface as well as conventional spectral-based image analysis. The system is comprised of a microcomputer, LSI based image processor and a hard disk of large capacity (300 MB), and an optical disk drive with 650 MB capacity.

This paper will discuss the concept and capabilities of microTULIPS. The system integrates powerful spatial information extraction methods based upon "Pixel swapping" as well as conventional spectral spatial image analysis methods. It also provides user-friendly interface to assist in terrain information extraction and utilize a prior knowledge of terrain to aid in interpretation.

EVOLUTION OF EROSIONAL PLAIN-TERRACES IN
SOUTH AND SOUTHWESTERN QATAR PENINSULA
FROM THE INTERPRETATION OF REMOTELY-SENSED DATA

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SUMMARY

Most of the surface of Qatar Peninsula is primarily composed of dolomitic limestone of the Lower Eocene Dammam formation, and is dominated by stony and sandy desert. In the south and southwestern parts of the peninsula, the monotony of this almost flat subdued landscape is broken by low rocky hills reaching a height of 103 m. They form conspicuous landforms of mesa-type hills, buttes, and knolls of Miocene and Miopliocene sediments, forming the Dam and the Hofuf formations respectively. The present-day configuration and distribution of the outcrops of these formations are attributed to various agents and geoenvironmental processes including the integration of paleogeography, transgression-regression of the sea, and the neotectonics.

In the present work, digitally enhanced Landsat MSS and Tm images have been interpreted to delineate the distribution pattern of the erosional terraces in the southern parts of Qatar Peninsula, and to investigate their evolution in relation to regional exposures and structures. Since the surfaces of these terraces are truly bedrock, their boundaries can be traced with accuracy using stereoscopic vertical aerial photographs. The latter have been helpful in delineating the regional lithomorphological boundaries of four well defined terraces in both the Dammam and Dam Formations.

The results of this work suggest that a marine transgression took place during the late Pliocene times, partially influenced by neotectonics related to the Zagros collisional orogeny. This was accompanied by partial erosion of the carbonate and lagoonal sediments of the Eocene Dammam and the Miocene Dam Formation, together with the continental Mio-Pliocene Hofuf Formation. This was associated with the creation of some steep erosional escarpments and a relatively large abrasion plain. Field observations verified this interpretation hypothesis, and prove its applicability all over Qatar Peninsula.

IHS TRANSFORM AND ITS APPLICATION TO
THE EXPLORATION GEOLOGY

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SUMMARY

The IHS transform and its application to the exploration geology have been studied with the TM CCT data in Xianju, Zhejiang province. The author has discussed the transformation with the chromaticity coordinate and different IHS transforms have been compared. The transform equations which can be conveniently used in the remote sensing digital image processing have been put forward and tested.

With respect to Kuochang Mountain, Xianju region, which is the major area for mineral exploration in Zhejiang province, satisfying results have been achieved in the investigation of color image saturation enhancement and multiple display of remote sensing TM image, geophysical and geochemical data.

Results show:

1. With the saturation enhancement through IHS transform, we achieve very good color image which, in general, is hard to get since highly correlated images can be observed among different TM wavebands. Hence, obvious advantages can be obtained in the geological interpretation.
2. It is very effective to use this transform in the multisource geoscience data analysis and display.

Through the multiple display of remote sensing, geophysical and geochemical data, a major geological linear fracture become quite prominent on the IHS composite image. It also clearly demonstrates the coincidence of aeromagnetic anomalies with remote sensing circular features and the relationship between geochemical anomalies and intrusive body. With these and geological analysis, we give out three prospective sites for mineral exploration.

In conclusion, IHS transform is a significant and practical method for the color enhancement of the digital image. Besides it opens up a new path for the multiple display of different remote and non-remote sensing data.

A REVIEW OF TECHNIQUES FOR IDENTIFICATION OF FAULTS ON
ACOUSTIC IMAGES FOR USE IN GEOLOGIC SPATIAL ANALYSIS

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SUMMARY

Three-dimensional subsurface locations and orientations of crustal fracture systems are essential for the exploration and development of economic mineral deposits, location and recovery of hydrocarbons, assessment of underground structures for waste applications, analysis of large scale aquifer systems, and basic geologic mapping. Fault recognition keys that have been utilized for the identification of faults on acoustic images include: 1. offset of reflectors, 2. presence of diffraction patterns, 3. possible reflections from fault surface, 4. projection of a shallow fault to depth, 5. variation between borehole data and seismics, 6. misclosure around a loop of profiles, 7. rapid changes in dips, 8. double reflections, 9. reflection of refracted wave from the fault surface, 10. blank or confused zone, 11. amplitude changes of reflectors, 12. inverse models, 13. refraction along fault, 14. refraction across fault, 15. changes in frequency of reflectors, 16. seismic geohistory, 17. apparent broad ramps at depth, and 18. geologic changes.

Most acoustic studies produce two-dimensional profiles, either obtained from the Earth's surface, or by using vertical seismic profiles. The trace of the fault on the profile can be observed, but its full three-dimensional orientation can not be directly determined. Recent developments in acoustic imaging techniques include high resolution three-dimensional capabilities. However, faults are depicted in these data bases as traces on a two-dimensional profile or horizontal slice through the data base. Cross hole seismic surveys tend to yield information on the general location of fracture systems at depth, but not their orientation. Advanced borehole acoustic tools locate fractures in the borehole, but do not yield their orientation. Televiewer methods produce the local three-dimensional location and orientation of fractures, but not their continuation over large areas.

WSU and Geologic Analysis and Consulting Services, in conjunction with Battelle PNL, is developing an advanced three-dimensional spatial correlation technique, geological spatial analysis (GSA), in order to define the subsurface location, orientation, and characteristics of fractures. GSA is focused on conducting comprehensive analyses using geologic data sets that can be referenced by latitude, longitude, and elevation/depth such as acoustic images, digital elevation models, earthquake foci, mapped faults and fractures, and lineaments. Based on these

data, the GSA techniques determine the location and orientation of structural features in three-dimensional space in order to develop a geologic model for the user.

The concept of combining acoustic images with other GSA methods has been tested in northeastern Washington state. A series of COCORP seismic reflection profiles have been acquired for the area. The acoustic profiles were visually analyzed for evidence of fault systems, based upon the above criteria. The region was also analyzed using a digital elevation model, which was automatically examined for fracture controlled stream drainages. The resulting GSA defined fractures correlate visually with previously mapped faults as well as the COCORP defined fractures. Computer software is currently being developed as a part of the GSA research that will automatically perform the comparison and processing of fracture traces observed on all these data bases simultaneously, uniquely defining those structures observed in multiple data bases.

DIGITAL PROCESSING AND ANALYSIS OF AIRBORNE MULTISPECTRAL DATA FOR
MAPPING HYDROTHERMAL ALTERATION AT YERINGTON, NEVADA

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SUMMARY

A high-resolution airborne multispectral scanner of GER, covering the wavelength between 500 and 2,500 nm with 63 channels, was flown over the Yerington mining area in Nevada to test and develop a new airborne survey technique for alteration mapping. The airborne data obtained over exposed hydrothermal alteration zones in the area were processed and analyzed to delineate alteration patterns through a computerized technique for spectral discrimination of individual minerals. The study includes digital processing and computerized interpretation of the airborne data along with field spectral measurements and verification work to correlate and evaluate the analytical results of the airborne data. The study result has demonstrated the applicability of airborne multispectral data to minerals exploration in obtaining detailed reconnaissance information on surface alteration. The aircraft height and scanner speed were set to allow data acquisition with an average pixel size of about 20 meters in azimuth and 15 meters in range direction.

The original data acquired have to go through several kinds of primary calibration and data reformatting prior to spectral analysis and image processing. These calibrations include dark current correction to remove electronic striping effects, time constant correction to remove the lag effect caused by electronics response time, roll correction to remove the aircraft roll effects, and subsequent conversion of the instrument counts to radiance. The logarithmic residual method was then applied to transform the data into probable spectral reflectance curves, removing the effects of atmospheric absorption and scattering as well as reflectance variations accruing from topographic features.

The data primarily processed by computers were used to determine the spectral properties of alteration minerals as they appear in measurements over the field. The technique developed in the study allowed the resultant spectral reflectance curves to be compared and matched with reflectance spectra of individual alteration minerals. This second step of the airborne data analysis involved identification of absorption positions by averaging differentiation followed by correlation of the resultant spectral curves produced through the above calibrations and processing to the standard reflectance spectra. The standard reflectance spectra were simulated from the field spectral measurements by resampling the digital readings into the same wavelength

centers as the airborne multispectral scanner, consequently enabling the correlation coefficients to be calculated between the two spectral curves. Identification of alteration minerals was done separately in VNIR and SWIR regions; the former for broad absorption features caused by iron oxides and the latter for sharp absorption by clay minerals and carbonates.

Both airborne remote-sensing data and field spectral measurements have thus helped produce alteration maps of the Yerington area, which also proved to be so accurate by field verification works as can be used for narrowing down the target in reconnaissance stage of minerals exploration.

DETECTION OF CHEMICAL AND PHYSICAL ZONATIONS WITHIN ASH-FLOW SHEETS

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SUMMARY

Many large ignimbrites within southern Nevada have pronounced vertical and lateral zonations. Chemical variations in ash-flow sheets have been related to compositional zoning in the pre-eruptive magma body. Physical variations within ash-flow sheets result from variations in primary depositional and cooling processes. Both Thematic Mapper and SPOT data are utilized to aid in detecting these zonal features. This paper describes the methodology for the calibration, enhancement and effective display for a photogeologic image interpretation.

Calibration of Thematic Mapper data was performed by simulating TM spectral bands from laboratory and field reflectance data. These values were then used in a linear regression model to convert digital values into percent reflectance. A canonical analysis was performed on the TM data and selected TM bands were merged with stereographic panchromatic SPOT images for photogeologic interpretation.

Results indicate that the spectral resolution of the Thematic Mapper data and stereographic capability of SPOT, with appropriate digital image processing and photogeological techniques, permit the detection of zones within ash-flow sheets.

TM-LANDSAT IMAGERY FOR FLUORITE EXPLORATION,
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SUMMARY

The use of TM-LANDSAT imagery supported by infrared aerial photographs has permitted the systematic identification of regional lineaments associated with fluorite mineralizations in the State of Santa Catarina, Brazil. More than one dozen fluorite and/or barite occurrences were discovered in structures identified in this manner, from which one large deposit was tested by diamond drill holes. The genetic conceptual model of fluorite mineralization in this region, as defined by previous geological works, clearly pointed out the close relationship of the mineralization with the mesozoic regional brittle shear zones. These zones represent the end product of proterozoic ductile shear zones reactivated during the Mesozoic times. Based on the information provided by the fluorite ore deposits it became possible to successfully test the application of TM imagery to identify the already known structures. Afterwards, the same method was used to prospect unknown areas. In spite of these structures being of a great longitudinal dimension (up to 30 kilometers), they are of difficult identification even in the field, as well as in the available aerial photographs for the region: 1:25,000 panchromatic black and white and 1:50,000 infrared coloured. The choice of the TM sensor and the manner of identification of lineaments by their topographic and spectral characteristics are discussed. This identification is made with help of the synoptic vision that the imagery can provide. The greater reflectance of the lineaments, where they are positive topographic is caused mainly by the presence of siliceous fragments and other hydrothermal minerals and the poorer vegetation. Where the topographic expression was negative, the spectral response is not clear: only the minor reflectance caused by the vegetation with excess of moisture, particularly in the 5 and 7 channels, was detected. The products of the sensor TM-LANDSAT (channels 3, 4, 5, and 7) were used and treated by the image processor image-100 (INPE-MCT), which make use of contrast stretch and directional filtering. The photointerpreted lineaments were transferred to infrared aerial photographs to make their correct localization easier. Field work not only proved the existence of many of the structures suggested by the photointerpreted lineaments but also permitted the discovery of the cited mineral occurrences.

DIMENSIONALITY REDUCTION AND COLOR COMPOSITE IMAGING
USEFUL FOR GEOLOGICAL APPLICATIONS

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SUMMARY

A novel method of reducing n-dimensional data and making color composite images useful for geological applications is proposed. The method consists of reducing n-d image data to 2-d data, which in turn is enhanced to a 3-d color space, representing the primary colors - RED (R), BLUE (B), AND GREEN(G).

The principles of PERSPECTIVE PROJECTION model is used to reduce n-d data to 2-d space. A newly defined TRIANT SPACE (trisecting the plane into zones of 120 degrees each) method enhances the 2-d space to 3-d color space of RBG, enabling color composition.

Most of the color composite imaging techniques use band manipulation procedures which require prior knowledge of the image under study. On the other hand, the method using PRINCIPAL COMPONENTS involves a 'time complex' statistical algorithm. The proposed method is simple and does not require prior knowledge of the image. Several examples have demonstrated the fact that the three primary color components of RGB are better than the first three principal components from the point of view of recognition and display.

Algorithm models for DIMENSIONALITY REDUCTION:

Let $(X_1, X_2, X_3, \dots, X_n)$ be the feature values of a pixel in n-space.

Two algorithms are proposed to reduce this data to 2-d data of type (Z_1, Z_2) .

ALGORITHM 1:

The unique TRIPLETs of the type $(X_1, X_2, X_3), (X_4, X_5, X_6) \dots$ are formed with necessary end corrections to compensate for an incomplete triplet that could possibly result due to n modulo 3 not being equal to zero. Each triplet is reduced to a DOUBLET by heuristically treating the triplet as a point in 3-D geometric space and mapping it to a 2-D plane using the perspective projection model.

From the resulting space of doublets, triplets are again formed with necessary end corrections, and the procedure is applied recursively until n-d is reduced to 2-D.

ALGORITHM 2:

The distinct triplet combinations of the type (X_1, X_2, X_3) , (X_2, X_3, X_4) , (X_1, X_2, X_4) , (X_1, X_3, X_4) ... are formed. Using the perspective projection model, an i -th triplet is reduced to a doublet (Z_{i1}, Z_{i2}) . The computations are repeated for all triplets to finally give a 2-d space of the type (Z_1, Z_2) where

$$Z_1 = \Sigma Z_{i1} \text{ and } Z_2 = \Sigma Z_{i2}$$

Algorithm model for color space generation by DIMENSIONALITY ENHANCEMENT:

After dimensionality reduction, each pixel is a doublet of the type (Z_1, Z_2) . The vector due to any distinct doublet is heuristically treated as the summation of two vectors stretched in opposite directions in a quadrant space and these two vectors are resolved further into four components.

If in general, P_1, P_2, P_3, P_4 represent the quadrant space components, then the primary color components as defined by the triant color space are -

$$R = P_1 + (1/\sqrt{3}) * P_2 + (1/\sqrt{3}) * P_4$$

$$B = (2/\sqrt{3}) * P_2 + P_3$$

$$G = P_3 + (2/\sqrt{3}) * P_4$$

These RGB components are used for color composition.

CONCLUSIONS:

Experiments performed on several simulated and remotely sensed multi-dimensional data have demonstrated that the algorithms proposed are efficient towards -

- i) dimensionality reduction and classification of n -space data
- ii) preparation of color composite images.

The proposed method finds applications in mapping, image analysis, photogeology and image interpretation with reference to airborne geoscience measurements and integration of remotely sensed geophysical data.

NEW THEMATIC MAPPING OF NORTHERN VICTORIA LAND (ANTARCTICA)
FROM SATELLITE IMAGERIES

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SUMMARY

The aim of this study is the evaluation of satellite imageries (MSS, TM, and SPOT data) of Northern Victoria Land (Antarctica), testing the geologic validity of satellite information and the feasibility of using such information to produce a geological map.

The study area is the sector of Northern Victoria Land bounded by the Reeves Glaciers Southward and the Mountaineer Range northward. The 90% of the surface is covered by ice, so in the satellite imageries there are pixels representing ice (85%), pixels representing mixed ice and rock (called "mixed pixels", 10%) and, finally pixels representing cropping out rock (5%).

We pointed our attention at the determination of a "level of confidence" that should allow the separation of rock from ice when the pixel contain both spectral "signs" ("mixed pixel"). First, we statistically classified the satellite imagery's pixels in four classes: 1) ice; 2) rock; 3) ice plus rock; 4) other. This step has made us able to identify and to classify the spectral "signs" of ice and rock respectively; then, an easy model is proposed, in order to calculate the percentage of ice and rock in mixed pixels: the model, which also takes into account the effects of relief and shadow, was tuned through aerophotographs and maps.

A thematic map was obtained with the maximum enhancement of information concerning rocks; in order to support the geologist in the interpretation of different types of rock, the very small spectral variations of classes was enhanced by IHS elaborations of the bands, emphasizing in "H" the spectral difference and reducing in "I" the illumination factor. The map was drawn in Polar Stereographic Projection at a scale of 1:250,000.

As a final result the obtained map was compared with the existing cartography of the study area, obtained with traditional methods, and an evaluation of the differences was done.

This work is included in the P. N. R. A. (the Italian National Research Project in Antarctica) geological researches on Northern Victoria Land.

LATE CENOZOIC STRIKE-SLIP AND NORMAL FAULTS REVEALED BY
ENHANCED LANDSAT IMAGES, MOJAVE DESERT, CALIFORNIA

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SUMMARY

Previously undocumented strike-slip and normal faults that extend up to 25 km in the central and eastern Mojave Desert have been revealed on Landsat Thematic mapper images enhanced by the four-component method, using three band-ratio components and an albedo component. The faults are perceived on the images because of spectral contrasts primarily at wavelengths longer than the visible. The faults are not obvious on aerial photographs or on radar images, but their presence has been confirmed by field investigations. These newly discovered faults are located in the Bristol Mountains-Lava Hills, Cady Mountains, and intervening valleys.

The newly identified faults provide important insights to the late Cenozoic tectonics of the Mojave Desert Block. First, these structures are part of a complex regional network of right shear that connects faults of the Death Valley region with the San Andreas Fault System. Second, some of these newly identified faults bound blocks that have experienced different Neogene rotation histories. These faults have likely served to accommodate those motions. Third, timing relations revealed along the faults suggest two intervals of movement. Faults located east of the Cady Mountains are overlain by unconsolidated alluvial fan debris (late Quaternary?) and are probably inactive. In contrast, most faults lying to the west and south of the Cady Mountains cut all deposits and are currently active.

LINEAMENT MAPPING FROM LANDSAT TM AND AIRBORNE C-SAR
OF PART OF THE SUDBURY STRUCTURE

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SUMMARY

Landsat TM and CCRS airborne C-SAR data of an area 15.3 by 15.3 km at the northeastern edge of the Sudbury Structure, were digitally enhanced. Geometrical correction was applied to the Landsat TM and airborne C-SAR. The resampling technique was cubic convolution interpolation. The enhancement techniques were contrast stretch, ratioing, filtering and principle component analysis. The linear contrast stretch with custom break-point was found to be a useful technique for geological purposes. The direction of schistosity, and the location of one olivine diabase dike can be observed directly in the images. Selected enhanced images and B&W airborne C-SAR image were examined in detail for lineaments. the number of lineaments derived from C-SAR image is greater than for Landsat TM, and the average lengths appear shorter. The area was divided into 4 subareas based on geology and lineament patterns. Lineaments were measured for both direction and length to construct rose diagrams in each subarea. The data was then correlated with existing joint and foliation data. The results show that the direction of inferred lineaments is consistent with field observations.

INTERPRETATION OF INTRABASIN STRUCTURES USING LANDSAT TM,
AEROMAGNETIC, AND GRAVITY DATA, ELDORADO VALLEY, SOUTHERN NEVADA

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SUMMARY

Frontier hydrocarbon and mineral exploration areas are often located within low-relief, alluvial basin settings possessing little or no subsurface stratigraphic or structural information. Knowledge of subsurface faulting is essential to any exploration model, particularly where faults and fractures are primary to the mobilization and/or trapping of hydrocarbons or mineralizing fluids.

The Basin and Range of Nevada is an example of a region whose alluvium-covered basins possess high potential for both precious metal and petroleum deposits. Detection of intrabasin faulting plays a significant role in exploring for placer gold and structurally-trapped hydrocarbons. Characteristically, basins are filled with alluvium of variable thickness that tends to suppress fault expression at the surface. Therefore, to locate faults at depth, it is desirable to use methods that have alluvium-penetration capabilities.

Three methods have been successfully employed in Eldorado Valley for interpreting intrabasin structures, primarily basement-related faulting. The methods include: 1) enhancement of digital Landsat Thematic Mapper (TM) imagery; 2) processing of gravity and aeromagnetic data; and 3) modelling magnetic flight line profiles. All data sets were utilized at identical scales to facilitate data integration.

Landsat TM imagery was digitally processed to enhance basin features. Reflection bands (1-5 and 7) detected drainage and compositional contrasts of pediment detritus. Direct evidence of basin structure was not evident on TM reflectance bands. However, Band 6 (thermal-infrared) proved extremely useful in detecting linear and near-circular features, which appear related to intrabasin structures.

U. S. G. S. gravity and magnetic digital data were obtained for the study area, gridded, and output in contour format. The gravity data set was complemented by 278 infill stations collected by Barringer Geoservices. Bouguer anomaly, residual gravity, and total magnetic intensity contour maps were generated and used for structural interpretation. In addition, alluvium thickness was estimated for the area through manipulation of magnetic data. Assumptions were that alluvium has little or no magnetic capacity, is rarely intruded by magnetic material, and

rests on volcanic and crystalline rocks similar to those in outcrop around the valley. Therefore, base of alluvium was considered to be the top of magnetic basement. Interactive profile modelling was performed on twelve magnetic flight lines to determine depth of alluvium and vertical configuration of basement rocks. These profiles proved useful for interpreting vertical-offset faulting and basement high and low features. The magnetic inversion appeared to be more diagnostic than thickness estimated from the gravity data, owing to interference from large gravity anomalies caused by volcano-tectonic features.

Integration of all interpretation provides a detailed model of intrabasin faulting and basement-related features. In some areas, alluvium was found to be surprisingly thin, whereas at other sites it was estimated several thousand feet thick. Features that may have been paleochannels were also observed. These results are important in planning both hard rock and dry placer gold exploration programs. Identification of structures would also benefit hydrocarbon exploration efforts by locating areas for seismic or geochemical surveying. Such structural features would also be expected to control groundwater movement within the alluvium and would bound areas of high groundwater capacity.

MULTISATELLITE IMAGERY FOR GEOLOGICAL MAPPING IN SAVANNA REGION OF
JUBA-TORIT-NIMULE-YEI AREA IN EQUATORIA REGION, SOUTH SUDAN

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SUMMARY

The regional mapping and study of the Juba-Torit-Nimule-Yei area represent an ideal case for the application of Landsat imagery interpretation in the tropical and savanna area of the Southern Sudan, which is inaccessible during the long rainy season. The implementation of this investigation was carried out through the Landsat imagery interpretation in both the dry and rainy seasons, together with aerial photographs, ground field work along possible roads and tracks and extensive laboratory analysis. Maps have accordingly been compiled for the geological and environmental units: structural lineations, lineation density, surface drainage, surface water, ground water potentials and laterite cover, soils, land use and vegetation cover. In this study land use, vegetation cover and soils (lateritic soils) are described. Landsat imagery interpretation has thus provided, within 2 years, including the compilation of the maps, a regional picture of an area of ca 30.000 sq. kilometers at the scale of 1:250,000.

CRETACEOUS-TERTIARY TECTONIC DEFORMATION IN TIERRA CALIENTE
MICHOACAN AND GUERRERO STATES, MEXICO

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SUMMARY

Interpretations of Landsat Thematic Mapper images, combined with field investigations in two 30 x 30 km areas near Ciudad Altamirano, are in progress to improve understanding of regional structure and tectonics of central Mexico. Information on thickness, attitude, relative age and lithology of individual units was gathered; and structural cross-sections were drawn, in order to understand the sequence of deformational events in the area and to improve existing geologic maps. The areas also served as test areas for evaluating geologic utility of remote sensing methods in central Mexico. We found that deformation in the region correlates well with variations in relative plate motion between North America and plates in the Pacific.

Post-Campanian folding and thrusting deformed the Mesozoic sequence, causing a major unconformity. Folds related to this event have axes trending approximately north-south. High-velocity, east-west convergence with the Farallon plate began about 70 Ma and may have been associated with the post-Campanian deformation. A thick sequence of mostly continental clastics (the lower member of the Balsas Formation) was deposited above the unconformity. These clastics were also folded, but with axes that trend northwest and interfere with the older structures. This folding may have been caused by a change to northeast-directed convergence with the Farallon plate, which occurred sometime prior to 40 Ma. Similar refolding may be expressed in the vicinity of the Chilacachapa anticline, about 80 km to the east of Ciudad Altamirano. A second unconformity was thus formed, separating the lower, deformed member of the Balsas Formation from an upper, less deformed member. Additionally, several minor unconformities within the upper member of the Balsas Formation were caused by continued tectonism. We interpret tilting of fault blocks of various sizes within a distributed, WNW-ESE trending zone of left-lateral shear as the dominant style of deformation during this period, which lasted until about middle Miocene time. The faulting was probably related to eastward motion of the Chortis block, as the southern margin of Mexico was gradually truncated and exposed to

subduction from west to east. Younger right-lateral faults, also trending WNW-ESE, appear to reflect a period of extremely oblique subduction of the Cocos plate between 12 and 7 Ma.

APPLICATIONS OF SATELLITE REMOTE SENSING TO STUDIES OF
CHINA CLAY WORKINGS IN THE SOUTHWEST OF ENGLAND

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SUMMARY

The china-clay workings of Cornwall and Devon are striking features of the landscape in remotely sensed imagery, and the dynamic nature of pits, dumps, and tailings dams, combined with the variety of different mineral assemblages exposed at the surface, makes them suitable targets for mapping and monitoring using remote sensing.

This study concentrated on the Lee Moor workings in South Devon, for which seven dates of Thematic Mapper imagery between 1984 and 1988 are held in the NRSC archive. A hierarchical classification procedure, separating firstly the areas of mineral workings from surrounding unworked land, then using mixture modelling to subdivide the mineral workings into areas predominating in mica, kaolin, and quartz, resulted in acceptable and repeatable mapping accuracy except in areas of deep shadow on pit and dump flanks. Classification accuracy was slightly improved by incorporation of a digital elevation model to compensate for variations in slope and aspect, although the need for updated DEM's of pits and dumps negates the cost-effectiveness of using remote sensing for monitoring changes in workings. For detection of time-related change, the use of band ratios was found to minimize differences between scene dates to acceptable limits, without the need for time-consuming atmospheric corrections. Three-dimensional views generated from combinations of satellite imagery with digital elevation models have proved a valuable demonstration of the contribution that remote sensing can make to the visualisation of the consequences of planning proposals.

SPOT IMAGE DATA AS AN AID TO STRUCTURAL MAPPING
IN THE SOUTHERN ARAVALLI HILLS OF RAJASTHAN, INDIA

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SUMMARY

The 10 to 20 m resolution of SPOT image data, together with their potential for stereoscopic viewing provides an excellent base for geological mapping in remote and rugged terrain that is akin to high-level aerial photographs. Their large format (60 x 60 km) also gives the advantages of synoptic coverage that ranks with images from the Landsat series of satellites. Use of stereo pairs of single-band SPOT images enables some revision of existing geological maps of the southern Aravalli Hills in Rajasthan at a scale of 1:100,000, and has added significantly to knowledge of their complex mid-Proterozoic structure. In particular, many possibly early low-angled faults have been discovered, together with the tectonic nature of a major terrain boundary, much detail of intricate structures has been added in the more remote areas, and a number of major cross-strike brittle fault zones that postdate the main ductile deformation in the orogen. The potential for lithological discrimination of multispectral SPOT data is severely limited by its restricted coverage of geologically important spectral features, and it is far surpassed by that of Landsat Thematic Mapper data, which would have been capable of more comprehensive lithofacies reconnaissance, had they been available. However, the abundant information on topographic texture and drainage patterns, the excellent expression of relief by stereo SPOT image pairs, and the a priori knowledge of the rough location of stratigraphically important lithologies derived from earlier field workers do enable the major units to be identified and outlined in their correct location and disposition.

IMPLEMENTATION OF THE FAST FOURIER TRANSFORM FOR EXTRACTING
LINEAMENT INFORMATION FROM SATELLITE IMAGES

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SUMMARY

The Fast Fourier Transform (FFT) is performed in a ContextVision GOP-300 image processing system in order to obtain quantitative lineament information from LANDSAT-TM and SPOT-MX subscenes in SW Norway. The results showed good correlation between rose diagrams plotted from manually obtained lineament orientations and general trends revealed on FFT results.

The test areas selected for this study are located in the Precambrian basement and the southernwestern Caledonides in SW Norway. Exposed rocks are predominantly migmatitic gneisses with penetrative regional foliation. They display characteristic structural features of the Caledonian deformation. Thus, the test areas provide both foliation and fracture zones related to the high and low spatial frequency, respectively.

The FFT algorithm performs a two-dimensional, discrete Fourier transform of grey-scale images. Since geological structures and features can be observed as edges and lines on satellite images we can employ the FFT algorithm to gain more quantitative information on distribution, orientation, and spacing of lineaments. FFT spectras were subsequently filtered with a moving average filter to smooth the noise generated complexities in the spectra. Spectras were color coded to indicate variations in spectral energy. Foliation performs as high spatial frequency component in the FFT spectra due to its closely spaced regional distribution. Therefore foliation related spectral information is located in the outer zone of the spectra. The dominant orientations appeared as spectral peaks.

OUACHITA MOUNTAIN THRUST FRONT: A DELTA STRUCTURE INTERPRETED THROUGH
INTEGRATION OF THEMATIC MAPPER, SEISMIC, AND WELL-LOG DATA

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SUMMARY

The thrust front of the Ouachita Mountains in western Arkansas is defined by the prominent asymmetric Washburn anticline. Previously interpreted as a complexly thrust-faulted anticline, the feature has been reinterpreted as a delta or triangle structure based on integration of surface mapping from thematic mapper (TM) data with subsurface interpretation of seismic and well-log cross sections.

The northern limb of the Washburn anticline consists of a relatively unfaulted, steeply north-dipping sheet above a major north-dipping backthrust. The southern limb consists of several steeply south-dipping thrust sheets that form a duplex zone in the center of the delta structure. Seismic and well-log interpretations suggested the presence of the imbrication in the core of the structure, but poor seismic resolution within the structure made interpretation of the back thrust and duplex geometry difficult. Surface mapping from TM imagery indicates the presence of the back thrust and the extent and geometry of the delta structure. Thrust sheets and horses also crop out, and their geometry is a guide to interpretation of subsurface data sets.

The new model of the Ouachita thrust as a delta structure has aided in subsurface data analysis and has resulted in a better understanding of trap geometry and distribution. This study also demonstrates the application of detailed surface mapping from satellite remote-sensing data to prospect-scale analysis.

APPROACHES TO INCORPORATING SATELLITE REMOTELY SENSED
DATA AS INPUT INTO GEOGRAPHIC INFORMATION SYSTEMS

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SUMMARY

Geographic Information Systems (GIS) represent a technological development of great potential for integrating remote sensing data with more conventional data sets. The purpose of this paper is to demonstrate a methodology for retaining maximum geological information from remotely sensed data while at the same time reducing the data into a format that may be easily imported into a GIS.

Two approaches were taken for this study: 1) directly importing processed data into the GIS thereby retaining digital values for each pixel and; 2) entering interpreted information from an analogue format into the digital database. The study area chosen for this project was the Baie Verte Peninsula, Newfoundland, an area of intense gold exploration. Rugged topography and limited access make this region difficult to survey through conventional fieldwork, therefore remotely sensed data are a welcome addition to previously existing data sets. The SPANS (Spatial Analysis System) GIS was used for the investigations.

The two approaches rely on using standard remote sensing software in a P. C. environment to analyze the data. Direct importing of the data requires processing such as principal component analyses and band ratios to reduce the volume of data to be imported. For direct import into the SPANS system the data must then be further reduced into a limited number of thematic classes. Clustering procedures such as classifications and density slices can then be applied to the data to reduce it to the appropriate number of classes. Advantages of this method include retention of digital values assigned to the data and easy portability into the GIS system. Interpreted data are input either as points, lines, and/or polygons. The advantages of visual interpretation of analogue products are that textural changes in addition to spectral differences will influence the interpretation, and the boundaries of classes will be generalized, facilitating easier comparison to other data sets.

The conclusions of this study are the following: 1) direct import is the most time efficient method of handling the transfer of information from most types of remotely sensed data to geographic information systems, 2) visually interpreted data provides discrimination of significant information on spatial/textural as well as spectral characteristics.

INTEGRATION OF REMOTE SENSING, GEOPHYSICAL AND GEOCHEMICAL DATA
FOR MINERAL EXPLORATION: A TEST CASE IN THE ABITIBI AREA, QUEBEC

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SUMMARY

For an area of the Canadian Shield covered by dense vegetation, with few visible outcrops, the use of multisource data, processing and integration is essential for the production of a more comprehensive geological map and provides clues to the mining exploration companies.

Digital data from remote sensing, aeromagnetism, and geochemistry were available. Analog data such as geological contours and mineral occurrences were digitized and used at different stages of the operation. Once time and money have been put forward to set up a good digital data set, many advantages appear: treatment and manipulations are easier. Digital information ensures the best individual treatment, allows a better visualization and correlation between different parameters and permits a statistical analysis of the whole set of data.

The test area covers 30 km x 30 km in the vicinity of the Joutel mining camp. First, each parameter was thoroughly studied. Landsat TM and SPOT images were processed and refined: principal component transform, edge enhancement, stereoscopic viewing, and lineament interpretation were performed. At the same time, digital aeromagnetic and pedogeochemistry data were processed to obtain enhanced total magnetic field maps, vertical magnetic gradient maps, and nine element geochemical maps.

The structural analysis from the remote sensing data shows four main directional patterns: WNW, NW, NNE, and NE. The aeromagnetic data and maps confirm the same structural pattern. The geochemical data analysis reveals three well-correlated elements (Co, Ni, and Zn). The distribution of these three elements shows several areas with a better potential for mineral deposits. Some geochemical anomalies correlate with known occurrences and deposits. New geochemical anomalous areas of the same type are found elsewhere. The treated magnetic data provide lithological information to add to the geological maps which are rather poor because of lack of outcrop. We were able to redraw more completely the geological map.

Some known mineral occurrence are controlled by a NW structure: the Harricana fault. New lineaments oriented NW and revealed by the remote sensing and aeromagnetic data are of primary interest for the mining exploration companies. A summary map was prepared to show priority targets based on the main lineament intersections and a favorable geochemical environment.

APPLICATION OF DIGITAL ELEVATION MODELS IN GEOPHYSICAL DATA PROCESSING

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SUMMARY

Digital Elevation Models (DEMs) can now be efficiently and economically derived from satellite data using automatic correlation techniques. This opens new possibilities for their practical application in many areas where elevation information is important in data processing and interpretation.

This paper presents an example of application of DEM in processing and interpretation of aeromagnetic surveys. It describes the development of a system for merging a DEM, derived automatically from SPOT data, with aeromagnetic survey data over the Queen Charlotte Islands, B. C., provided by the Geological Survey of Canada. From the DEM and radar altimeter data recorded during the survey the altitude of the sensor above the mean sea level is derived.

The absolute altitude is then applied in the data processing and interpretation. In the processing stage, it is used for flight line intersection analysis and vertical gradient correction. In the survey interpretation stage, altitude values are used in reduction of data to constant altitude/terrain clearance, and in anomaly inversion.

Finally, the use of DEMs in processing and interpreting other types of geophysical surveys is discussed, including airborne gamma-ray spectrometer, airborne gravity, and dense surface gravity surveys.

EVALUATION AND COMPARISON OF LANDSAT TM, AIRBORNE SAR AND GEOPHYSICAL DATA
FOR REGIONAL STRUCTURAL INTERPRETATION, NORTHERN NEW BRUNSWICK

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SUMMARY

The structure of the study area in northeastern New Brunswick is dominated by the Rocky Brook Millstream fault system, a northeast trending transcurrent dextral shear zone. Previous studies have demonstrated geologic structures of certain preferred orientations control the location of base and precious metal occurrences in this area.

The area is underlain by three main geologic elements: the Ordovician Miramichi Terrane, the Ordovician Elmtree Terrane which is a tectonic inlier to the north, and a narrow belt of Silurian sedimentary rocks of the Chaleur Group which separates them. The Ordovician rocks record a complex history of multiple deformations whereas the Silurian rocks have been considered to contain only one generation of structures. New field evidence suggests, however, multiple folding and faulting events within the Silurian rocks.

Several types of spatial data were used to characterize the regional structure: LANDSAT TM imagery and airborne synthetic aperture radar (SAR), radiometric and aeromagnetic surveys. Each of the data sets were evaluated separately, registered to a common geographic base and then integrated using a microcomputer-based GIS to determine their combined effect.

IMAGE PROCESSING AND DATA INTEGRATION TECHNIQUES FOR IMPROVED GEOLOGICAL
MAPPING IN THE BUCHANS AREA, CENTRAL NEWFOUNDLAND

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SUMMARY

The central portion of the island of Newfoundland represents a remote, glaciated and heavily vegetated terrain where geological investigations are made difficult by a characteristic paucity of outcrop. As such, remote sensing data sets and digital image processing techniques represent a potentially valuable means of acquiring and analysing additional geological information for the area. The investigations have focused on demonstrating the value of three digital information sources - Landsat Thematic Mapper (TM), C-band synthetic aperture radar (SAR), and total field aeromagnetic data - through independent analysis, visual overlay and statistical integration. A classification strategy has been devised which utilizes an integrated spectral (TM)/aeromagnetic data set. Detailed spatial and statistical analysis of these two data sets has revealed the underlying relationships between them. The resultant classification improves the ability to map geology because it represents well those aspects of both the spectral response (regional geobotany) and aeromagnetic response which reflect the bedrock geology.

Both the aeromagnetic data and the SAR data have been used to define linear elements which have been found to control gold and base metal mineralization in the region. The aeromagnetic data set was enhanced using artificial illumination and false color techniques, and processed to investigate the information content of first and second order derivatives and frequency distributions derived as moment measures. The SAR data were very useful for delineation of subtle structural and lithologic (where surficial cover is thin) trends which are not evident on conventional maps or airphotos. In addition, the SAR data provide excellent characterization of geomorphologic features related to the last glaciation of the region and therefore can be of considerable benefit of drift prospecting.

In all cases the objective has been to augment rather than replace conventional methods. Findings have resulted in better understanding of the distribution of lithologic and structural elements within the study area, and therefore will be useful for defining future exploration targets.

DIGITAL INTEGRATION OF REMOTE SENSING AND GEOSCIENCE DATA FOR
THE GOUDREAU-LOCHALSH STUDY AREA, MICHIPICOTEN GREENSTONE BELT, ONTARIO

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SUMMARY

In 1987, the Ontario Geological Survey (OGS) and the Ontario Centre for Remote Sensing (OCRS) initiated a joint study to evaluate the digital integration of remote sensing into a geoscience data base. The study area was the Goudreau-Lochalsh site, located within the Michipicoten greenstone belt approximately 40 km northeast of Wawa, Ontario.

A high-quality geological data base exists for the area and large scale mapping was currently under way. The release of two other data sets was also imminent -- digital geophysical data and airborne radar data. The site also has high mineral potential. Intensive exploration and mine development are already under way.

The area has a long and complex structural history which has been studied and documented in some detail. Remote sensing data was expected to contribute to the interpretation of the local structural geology and, in the future, to the interpretation of the entire Michipicoten and Michibushu Lake greenstone belt.

The mapper in the field commonly relies on the use of conventional geoscience data such as existing geological and geophysical maps as well as airphotos. A mapping base for both the preparatory survey and the field mapping process is also relied on. Remote Sensing data has recently been included albeit in a relatively crude form such as a photographic enlargement.

The information content of remote sensing and existing geoscience data could be greatly improved if incorporated together within a digital geoscience data base. A digital image analysis system would provide the ability to enhance and analyze remote sensing as well as non-image data such as digitally recorded aeromagnetics. Geological maps can be manually or automatically digitized and stored in either raster or vector form. With a common geographic reference base, these digital data sets can be integrated thus allowing the geologist to apply conventional interpretive techniques over various data sets which can be viewed, superimposed and merged at various scales.

The most important element in the integration process is the creation of a hardcopy product customized to suit the geologists needs. The product should be a fully annotated map produced at field base scale. This can be readily accomplished with a high resolution electrostatic colour plotter.

The current study area contains the following digital data sets:

1. Landsat 5 TM
2. Airborne radar (C band SAR 5m. resolution)
3. Total field aeromagnetics
4. General geology
5. Surficial materials

The following merged data sets have been created and plotted in map format:

1. Landsat and airborne SAR at 1:25,000
2. Airborne SAR and aeromagnetics at 1:25,000
3. General geology and airborne SAR at 1:25,000
4. First derivative aeromagnetics and airborne SAR at 1:25,000
5. First derivative aeromagnetics, airborne SAR, and general geology.

From the integrated data, any combination among the data sets can be interactively created and plotted at any scale. When data sets are merged, each can still be viewed through the other(s).

The process for the creation of the computer generated maps and an assessment of the products for both field mapping and mineral exploration will be described in detail in the proposed paper.

FEATURE EXTRACTION OF VOLCANIC GEOLOGY AND STRUCTURE BY INTEGRATED
PROCESSING OF LANDSAT TM IMAGERY IN KUOCANGSHAN AREA OF ZHEJIANG

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SUMMARY

The study is a part of the national research project on Volcanic Geology and Mineral Resources. The Kuocangshan District is located in the southeast of Zhejiang Province and is a typical area of the volcanic action in Mesozoic volcanic rock zone in the Southeast China. To study the features of volcanism in this area by using new generation of remotely sensed data and geophysical data is highly significant for further researches and explorations.

The study involved enhancements of the LANDSAT TM image of the area, quantitative analyses of lineaments in the TM image, intensity-hue-saturation (IHS) transformation of the integrated TM image and aeromagnetic data, and feature analysis of volcanic geology and structure.

The area has been divided into several structural zones by results of the quantitative analysis of lineaments in the TM imagery. Most circular features and their patterns in the area have been illustrated in the image by the display and systematic interpretation of integrated data. Some volcanic circular structures, e.g. the Shangzhang Volcanic-Sedimentary Depression, the Kuocangshan Peak Volcanic Dome and the Liwan Caldera, etc., have been determined by combining the feature analysis of the image with the field investigation. Quite a few of volcanic strata in the area have been identified, even some distributions of these strata in the area were revised, by the analysis of imagery texture and hue as well as the field investigation. The volcanic stratigraphic sequence and overlap among the four volcanic cycles in the area have been recognized by the integration of imagery features and spatial patterns of volcanic circular structures. A large circular feature surround the Kuocangshan District has been verified to be a huge and regional volcanic-tectonic upheaval. Several problems about volcanic geology and structure in the area have been solved.

The result of the study have shown that the integrated processing and feature analysis of LANDSAT TM imagery, and with aeromagnetic data, is an effective and practicable way to study the geology and structure in volcanic areas, and could provide some important and useful information for further mineral exploration.

ACCESS TO LARGE INTEGRATED SPATIAL DATA BASES THROUGH CD-ROM TECHNOLOGY

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SUMMARY

As we become more aware of the Earth as an integrated system, we want data appropriate for such study. Continued improvements in computer processing are hampered by traditional techniques of transferring data. Alternate methods of data transfer as through cartridge tape or optical disk are currently being considered.

Compact Disk Read-Only Memory (CD-ROM) technology is one option that is currently receiving considerable interest. Digital data/software can be combined with images and sound on one medium, storing about 600 megabytes of material. Unlike helical tapes and Write-Once-Read-Many (WORM) optical media, CD-ROM discs are standardized throughout the industry. They can also be reproduced inexpensively and efficiently compared with alternative media. The disadvantage that they cannot be written to is also an advantage, protecting archival data from corruption from overwriting. New read-write magneto-optical systems are currently under development and initial commercial release.

NOAA's National Geophysical Data Center has been producing CD-ROMS for almost three years:

1. Selected Geomagnetic and Other Solar-Terrestrial Physics Data of NOAA and NASA. Produced in cooperation with NASA.
2. Gloria Data, from the mission to image parts of the Gulf of Mexico's floor with sidescan sonar. USGS data are complemented with NGDC data management, display, and accession software.
3. Geophysics of North America. Commemorating the Geological Society of America's Decade of North American Geology, containing gravity, aeromagnetism, Magsat satellite magnetism, topography/bathymetry, seismicity, crustal stress, thermal aspect, AVHRR satellite imagery, and base map data.

4. Marine Geological and Geophysical Data from the Deep Sea Drilling Project (DSDP). A two-disc set containing data from this 15-year program. Includes a wide variety of data on hardrock and sediment geology, paleomagnetism, ages, thin section and other geological data plus bathymetry, magnetics, well logs and other geophysical data. Jointly sponsored with the Joint Oceanographic Institutions, Inc.

5. Future global change CD-ROMs? NGDC is producing a set of floppy diskettes of monthly normalized vegetation indices derived from AVHRR, plus associated terrain data from other sources to prototype CD-ROM development for the International Geosphere-Biosphere Program. This evaluation set may include analytical portions or IDRISI, a PC-based Geographic Information System from Clark University.

The current CD-ROM data discs are accompanied by software for displaying and accessing the data. One can select appropriate data for downloading into one's PC (or through the PC to another computer system over a network). The software is on floppy disks for easy modification and bug fixes, while the data are on CD-ROM for easy portability and protection of data integrity. Accession aids include basic time series analysis for the geomagnetism time series data; image display, earthquake plotting, and contour overlay for the geophysics of North America; and other appropriate software from the other discs.

Guidelines for the use of the discs will be presented.

We have learned several things about the production of such data on CD-ROM media, and will happily share such knowledge.

IMAGE PROCESSING APPLIED TO DIGITAL ELEVATION MODELS:
A USEFUL TOOL FOR STRUCTURAL STUDIES,
APPLICATION TO THE VOSGES MASSIF AND THE RHINE GRABEN (FRANCE)

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SUMMARY

Three-dimensional reconstruction techniques by digital processing of SPOT stereo images are now well improved. As a consequence, digital elevation models will be available in whole earth surface. They provide new prospects for exploration geology.

Nearly all lineaments mapped on synoptic-scale images are expressions of topographic features. Thus, it seems obvious, therefore, to include analysis of digital elevation data in regional phases of tectonic evaluations. These data may be processed and displayed using image processing techniques in a variety of ways to enhance terrain relief. Synthetic relief images, stereo pairs, shaded-relief images, or oblique perspective images are ideal data bases for detailed evaluations in such a way that the analyst can easily establish relationships between topography and other geologic conditions.

Moreover, the computing of the slopes characteristics (azimuth, dip, drop) by gradient operators, the automatic extraction of drainage networks, the classification of surface-specific points (peak, pit, passe, hillside...) using topological properties, the trend analysis lead to a semi-automatic geomorphological analysis. These treatments allow to detect topographic anomalies like steep slopes, circular features, and areas of homogeneous topographic texture. The geometrical organisation of the morpho-structural features (e.g. en echelon, Riedel faults in a shear zone) may be obtained by an autocorrelation process.

These treatments have been applied to a 50 by 50 km digital elevation model of the Vosges massif northern part (France) and allow to give new tectonic interpretations of this area.

SPOT IMAGE PROCESSING FOR GEOLOGICAL EXPLORATION IN INNER MONGOLIA, CHINA

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SUMMARY

Two scenes of SPOT-1 HRV-1 image data of different dates (May 7 and July 20, 1986), covering almost the same area in Inner Mongolia of China, are digitally processed for geological exploration. Image data of the first date include both the XS and P modes on CCT's and films. The second image in XS mode was acquired in photo films and later digitized for multitemporal computer analyses. The three image data sets are jointly processed and enhanced in 512 by 512 subscenes. Spectral information in the two XS images, spatial information in the panchromatic image, and temporal information derived by registration and combining of the two XS data sets are synthetically used for geological mapping and targeting of polymetallic mineral deposits in the area.

Various computer processing techniques, including contrast stretching, ratioing, principal component analysis, other orthogonal linear transforms, local enhancement and filtering, are applied to the image data. False color composites of two ratios plus one band, three principal components, and some other transformed axis images provide good lithologic separation. Linear, drainage pattern, and textural features are extracted from the high resolution P image subscenes and combined with multispectral information. The optimally enhanced subscenes provide much more new geostructural information to the detailed study areas. Lithologic and stratigraphic interpretations are much improved compared to the results derived from Landsat MSS and black-and-white airphotos. Up to the 12 litho-stratigraphic units in the area are clearly distinguished on the SPOT images. Owing to the high spatial resolution, the strata can be subdivided into formations according to different colors and morphologic characteristics.

Field checking proved the litho-stratigraphic interpretation and the existence of the many interpreted, previously unmapped, faults. Multitemporal analyses of the two XS scenes after geometric registration show small anomalous areas that are not detectable in one scene. Field check suggests that the anomalous spots are related to gossan outcrops, possibly associated with polymetallic mineralisation.

The image processing revealed the existence and characteristics of systematic noise within the Level 1b preprocessed XS data, mostly as banding or striping oblique to the line and sample directions. Experiments are made for suppression of the banding in enhanced images for better geologic interpretations.

THE GEOLOGICAL RELEVANCE OF LINEARS MAPPED FROM DIFFERENT DATA

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SUMMARY

Linears may be classified by their geometry, contrast, and genesis using satellite images, aerial photographs, or topographic maps. In an attempt to reduce the subjectivity of those attributes, a hierarchical classification was developed over the past 15 years. In the absence of geological observations, aeromagnetic data are the principal determinants of geological relevance.

In the analysis reported here, linear and curvilinear features were mapped from four sets of data for a common area near Halifax, Nova Scotia. These data comprised: a summer Landsat TM image, a spring Landsat MSS image, a winter Landsat MSS image, and topographic maps. The linears were mapped from the images using PROCOM-2 and all were entered into digital files for research concerning the use of micro-based spatial analysis for geological mapping.

Seventy-eight separate linears were mapped, of which fewer than 5% were recognized on all four sets of data. The percentage of linear recognized on only one set of data (and no other) were: topographic maps, 35%; winter MSS, 24%; summer TM, 21%; and spring MSS, 0%. On the other hand, only 10% of Landsat linears were not represented by an alignment of physiographic features on the topographic maps.

The geological relevance of linears was assessed by correlating the linears with aeromagnetic and geological maps. From the aeromagnetic correlation, 61% of the linears were interpreted as lineaments that represented faults (33%), foliation (14%), joints (10%) and intrusive contacts (4%). However, many of these features are not represented on published geological maps of the test area. Hence, all have not been validated. Several interpreted contacts correlate well with mapped boundaries of intrusions but there is little conclusive correlation for joints. Most interpreted foliation agrees in general with observed strikes. Fewer than half of the 14 defined and approximate faults were mapped as linears. Only 2 of 13 assumed faults were so mapped. Thus, less than one-third of mapped faults correlate with linears. On the other hand, at least 30 topographic linears have aeromagnetic correlations that suggest they may be unmapped faults. Of the nine linears that do represent mapped faults, all were defined from the topographic maps, five from the winter image, four from the summer image, and three from the spring image. Faults with a mapped length of less than one km were not well represented by any of the sets of data. Most known long faults (greater than 10 km) were not well represented either, possibly because they are mainly thrust faults in this particular case.

While operator and site bias has not been assessed in this study, the following conclusions are reached:

1. Topographic maps are the best single source of information about lineaments;

2. Correlation of linears with aeromagnetic data will confirm geological relevance, especially for faults and foliation;
3. The cost of mapping linears from topographic maps is about one-half to one-tenth that of mapping from remotely sensed data, primarily because of the cost of the data.

ON THE INTEGRATION OF SATELLITE DERIVED MAP DATA
INTO SPATIAL INFORMATION SYSTEMS

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SUMMARY

Voluminous amounts of data have been derived from various satellite imaging systems. In order to incorporate these data into a spatial information system, it is necessary that all of the data is referred to a common reference system. Since any coordinate system is likely to be time dependent as a consequence of network redefinition, readjustment, or other phenomena, the spatial components of the remotely sensed data are subject to variations or inconsistencies. Geometrical, topological, computation, and other considerations can be critical in the positional data revision in order to preserve the integrity and reliability of the spatial information system. A previously proposed strategy for such revision is presented and analysed in terms of datum transformations, regional discrepancies, and local distortions while preserving the topological relationships in as much as possible. In addition, the approach includes special considerations for non-control point entities which can be expected to require considerable computational effort. This methodology is actually an extension of a technique introduced by the second author for estimating corrections to mapping control, which has been used for years in various contexts. Experimental implementations of the proposed strategy are reported and recommendations for comprehensive production applications are included.

STRATIGRAPHY AND STRUCTURE OF THE KALPIN UPLIFT, TARIM BASIN, NORTHWEST CHINA

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SUMMARY

The Kalpin uplift, located on the northwestern margin of the Tarim basin, Xinjiang Uygur Autonomous Region, China, exposes a complete Paleozoic cratonal stratigraphic sequence. The lack of vegetational cover and the visible color contrasts between the stratigraphic units afford an excellent situation for detailed geologic mapping (1:250,000 scale) from Landsat MSS imagery.

The shallow-marine to nonmarine stratigraphic sequence includes metamorphosed Upper Proterozoic strata; Sinian (latest Proterozoic-Cambrian) clastics and carbonates; Cambro-Ordovician carbonates; Silurian green shales; Devonian redbeds; Carboniferous clastics and carbonates; and Permian carbonates, clastics, and subaerial basalts. Field transects through these strata, including reflectance measurements with an eight-channel (475-985 nm) Delphi hand-held radiometer, measurement of structural attitudes, and stratigraphic sampling, serve to constrain the geologic interpretation of the satellite imagery.

In the western part of the uplift, the Paleozoic rocks are exposed in a series of low, parallel, SW-NE trending, curvilinear ranges representing the fronts of four SE-verging thrust sheets, modified by strike-slip faults which trend normal to the thrust traces. The regular thrust repetition of the entire stratigraphic section suggests the presence of a detachment horizon within the Cambrian strata. In the northeast, a N-verging thrust sheet ramps up on Proterozoic and Lower Paleozoic strata probably deformed by a middle Paleozoic tectonic event. The Bachu uplift, another middle Paleozoic structure, trends perpendicular to the western thrusts, and is over-ridden by the most cratonward of the thrust sheets. The thin-skinned compressional style of the uplift reflects stresses transmitted from the Himalayan region, as the Indian plate continues to move northward. Deformed Neogene strata document this recent tectonic movement.

Potential petroleum source rocks in the Paleozoic section include Ordovician black shales and Carboniferous black limestones. Potential reservoir rocks include fractured and karstic Cambro-Ordovician carbonates and Carboniferous quartzose sands. The thin stratigraphic section exposed on the uplift appears non-prospective, but subsurface equivalents of these rocks to the west and east may be important targets for future exploration. Indeed, a major 1984 discover near Kuga, 350 km to the east, reportedly produces Ordovician-sourced oil from Cambro-Ordovician carbonates.

LANDSAT TM INTERPRETATION FOR HYDROCARBONS -
SOUTHWEST CANNING BASIN, WESTERN AUSTRALIA

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SUMMARY

Three and one quarter Landsat Thematic Mapper images covering 83,200 square kilometres (20 million acres) were interactively processed, printed, and interpreted at 1:100,000 scale covering two large oil exploration permits along the unexplored southwest margin of the Canning Basin in Western Australia. Only five oil exploration wells, few mineral exploration drillholes and no deep water wells have been drilled in this area of the Basin which contains prospective Permian clastic, Silurian evaporite, and Ordovician carbonate sediments. The TM imagery was processed to highlight tonal anomalies related to possible hydrocarbon microseepage from subsurface reservoirs.

Five summary maps at 1:500,000 scale were derived from the original 1:100,000 scale interpretation maps. They include interpretations of structure, fracture intersections, fracture density, tonal anomalies, and exploration leads.

The exploration leads identified include four salt domes, 15 anticlines and faulted anticlines, six tilted fault blocks, and one fault-controlled stratigraphic lead. Many leads have coincident tonal anomalies.

An additional interpretation of 1:1,000,000 scale "Quick Look" Landsat black and white imagery has led to a greater understanding of the tectonic environment of this part of the Basin. Post-Cretaceous fault blocks are evident as are possible strike-slip movements along the major northwest-trending basin-margin faults and northeast-trending cross faults. Both pre and post-Cretaceous movement is suspected on various diapirs.

Further fieldwork can be concentrated on the play types and leads identified by this remote sensing work, significantly accelerating exploration on these frontier areas where billion-barrel fields may still be found.

THE INTEGRATION GRAVITATIONAL-MAGNETIC AND REMOTE SENSING DATA
FOR RECOGNITION OF LOCAL PETROLEUM-PROMISING STRUCTURES

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SUMMARY

The suggested technique is based on analytical and numerical calculation of synthesizing conversion of gravity Δg and magnetic T fields into a special transform, or D-function. These numerical calculations are combined with seismic and drilling data and with lineament nets recognized on middle resolution "Sojus" space imageries. It has been used for a detection of faults and positive local structures prospecting for the oil and gas. D-function is the modules of the vector whose components K_x , K_y , K_z are obtained by solving a system of equations that link the gravity V and magnetic U potentials derivatives at the points of the problem area, or matched initial anomalies $\Delta g = V_z$ and $\Delta T = f(U)$:

$$\begin{aligned} V_{xx}K_x + V_{xy}K_y + V_{xz}K_z &= U_x \\ V_{xy}K_x + V_{yy}K_y + V_{yz}K_z &= U_y \\ V_{xz}K_x + V_{yz}K_y + V_{zz}K_z &= U_z \end{aligned} \tag{1}$$

In the case of a homogenous model of geological environments with constant rebumdant magnetization I to rebumdant density σ ratio for potential fields sources, the D-function is constant and equals $I/f\sigma$, where f is the gravity constant, and Eq. (1) coincides with the conversed and good known Poisson relation. In the case of inhomogeneous environments, or sources, where $I/f\sigma$ changed from point to point, calculated values of the synthesizing transform would be anomalous.

The whole point of the suggested technique is to compare some anomalous values of the D-function for certain points of the upper hemisurface with those for simple models of inhomogeneous environments presented either analytically or numerically. All the numerical algorithms were programmed for the EC-type computer in PL/1.

The results obtained have shown that at a certain value of physical parameters of gravity-magnetic sources, the values of the D-function at some levels of the upper hemisurface become anomalouse or infinitely large. That effect is the result of non potentially of the considered function and is regarded as a main criterion for the recognition of local structures. The reliability of recognition considerably increases when the geophysical results are integrated with lineament pattern or circular features interpreted from space imagery.

Several examples of integration Geophysical data with Remote Sensing are presented for the structural tectonic subdivision and petroleum exploration within Precaspian province.

DETECTION OF SURFICIAL CHANGES ASSOCIATED WITH HYDROCARBON
SEEPAGE, SHEEP MOUNTAIN ANTICLINE, WYOMING

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SUMMARY

Remote sensing is becoming an extremely useful exploration tool for the detection of hydrocarbon deposits. The purpose of this paper is to investigate the usefulness and limitations of remotely sensed data, both satellite Landsat Thematic Mapper and high resolution ground spectroradiometer data, in the detection of subtle surficial changes associated with buried hydrocarbon reserves.

The region chosen for this study, Sheep Mountain Anticline Wyoming, contains two producing oil fields, and several other oil reserves. Included in this region are well exposed sedimentary strata ranging in age from Mississippian to Tertiary.

Spectral signatures of Landsat TM data were examined for five distinct lithologies to determine if changes were apparent with increasing proximity to the oil fields. High resolution spectral data were collected from field samples in each of the five lithologic units and compared to the TM data.

Zones of surficial changes within a red-bed sandstone formation were identified with the Landsat TM data near a major oil field (Spence Dome). Bleaching of this iron-oxide rich formation was indicated by a decrease in the band 3/1 ratio in conjunction with an increase in albedo. This change in spectral signatures was also reflected in the high resolution field spectroradiometer data. Laboratory investigations indicate that the bleached region corresponds spatially to an absence of kaolinite in clay mineral assemblages in an adjacent shale dominated lithologic unit.

This combination of laboratory detected changes and the recognition of a bleached zone through remotely sensed data leads to the conclusion that hydrocarbon seepage has been active in this area. This seepage was not detected through field mapping indicating that the remotely sensed information proved to be an essential data source to detect subtle surficial changes associated with hydrocarbon seepage.

**LARGE SCALE APPLICATIONS OF REMOTELY SENSED DATA IN MATURE BASINS:
EXAMPLES OF THE BENEFITS OF BAND-BY-BAND INTERACTIVE ANALYSIS**

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SUMMARY

Interactive digital analysis of single band, ratio, and composite multi-spectral, multi-sensor, and multi-temporal satellite data is demonstrated to more clearly define surface conditions of anomalous appearances coincident with hydrocarbons at depth.

RECOGNIZING THRUST FAULTS AND EXPLORATION IMPLICATIONS

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SUMMARY

Oil fields associated with thrust belts have been found around the world, including the Canadian Rockies, the Wyoming Overthrust, the Ouachitas, the Potwar fold belt of Pakistan, the Oman Mountains, and in the Tarim and Tsaidam basins of China, for example. As a major player in thrust terranes, Amoco has recognized the usefulness of mapping thrusts and thrust-related features using remote sensing techniques.

Thrust faults as a class are among the most difficult to recognize by photointerpretation because the low angle of the fault plane causes the fault trace to follow topography rather than cut across it as a lineament. There are, however, several clues to recognizing thrusts from airphotos and satellite imagery. Thrusts tend to be convex in the direction of transport. In areas with good outcrops one can often recognize repeated section or abrupt changes in structural style, particularly changes from tight to open folding and from imbricate ridges to folding. Sudden deviations in strike and/or dip occur across thrust faults. Stacked thrust slivers have a characteristic ridge-forming topography. Imbricate fans tend to develop above ramps or subthrust anticlines, providing clues to subthrust plays. If the stratigraphy of an area is known, one may recognize thrusts on the basis of vegetation patterns.

Anticlines associated with thrusting often provide traps for hydrocarbons. Oil and gas pools can accumulate in anticlines both within and along the leading edge of thrust plates. Folds with amplitudes equal to or greater than wavelength (concentric folds) imply near-surface detachments, as do box and chevron folds. Asymmetric folds with common vergence suggest thrust or reverse faulting. Overlapping anticlines or synclines imply intervening thrust faults. Folds riding on thrusts generally verge in the direction of transport. Thus, drilling a successful well requires recognition that the structural high at depth is offset toward the backlimb.

SATELLITE IMAGERY INTERPRETATION OF SOME OIL AND GAS FIELDS
IN PAKISTAN: AND IMPLICATIONS FOR FUTURE EXPLORATION

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SUMMARY

The regional setting and geological history of Pakistan's over 800,000 sq. km. sedimentary area in terms of plate tectonics, and its resultant complex structural framework, makes the country a good candidate for satellite imagery mapping and interpretation for hydrocarbon exploration.

Pakistan is a proven hydrocarbon province of long standing, producing from about 60 oil and gas pools. Interpretation of some of these known deposits, representing varied geological settings, is attempted, using manual techniques of image analysis of computer-enhanced satellite imagery. Particular attention is paid to the recognition and interpretation of such regional structural features as folds, various categories of faults and fractures. Regional faults along plate margins are also traced from satellite images and available geological ground work. Attempts are also made to detection of surface alteration aureoles over some of these deposits, and around some known seepages.

These examples are then extrapolated to highlight areas of potential hydrocarbon accumulation. Cost-effectiveness of satellite imagery mapping in these areas, often remote and difficult to reach for ground work, is emphasized for planning surface geological and geophysical surveys.

The study of deformation style around the oil fields of the Northern Indus Basin indicates different structural styles for many anticlines than the existing interpretation based on surface geological work. These styles can be correlated to different basin movements. Some anticlines recognized in the northeastern and eastern parts of Potwar and the Trans-Indus part of this basin may thus become potential targets for hydrocarbon exploration.

The Landsat images of Dhodhak, Rodho, Sui, and Uch gas field in the frontal part of the Sulaiman foldbelt reveal an advancing deformation front. Continuation of the existing deposits at Zin, Loti, and Pirkoh structures in the compressional folds associated with regional thrusting is also possible to Bambar, for example. Folds north of the Dhodhak gas/condensate field, e.g. Domanda-Darazinda, and possible concealed structures in the plain area in front of the foldbelt also appear to have potential in terms of their regional setting.

In the Southern Indus Basin, some narrow anticlinal structures developed near Mazrani field in the frontal part of the Kirthar foldbelt catch the eye. Analogy of the Sukkur rift with Jaisalmir-Cambay rift system enhances its prospects. There is a possible rift block of the Kutch Basin in the southeastern part of the country which merits further attention.

Landsat images also highlight the structural styles in the Baluchistan Basin and may help to unravel the basin movements related to subduction, leading to a better understanding of the geology of this sparsely explored vast area. Small anticlines at the southern flank of the Kulanch syncline in Makran, and the thick sand-shale deposits of the region invite exploration. Presence of Paleogene carbonate inliers around Khara depression may lead to deep probing in the depression. Pattern of mud volcanoes recognized along the Makran coast also fit in the basin evolution.

Also in Baluchistan, a sizeable basin - Pishin, is traceable behind the Kirthar-Sulaiman foldbelt. Configuration of the Sibi Basin, flanked by Tertiary marine rock outcrops also merits attention.

In the north-west frontier province, the Peshawar-Haripur intermontane basin, which is filled with alluvium, may also be prospective, as the older sedimentary rocks of Hazara seem to continue under the alluvial cover.

These leads from satellite imagery interpretation need substantiation by systematic ground work and analysis of rock samples for source and reservoir potential, further delineating promising areas for seismic surveys, leading to the identification of drillable prospects. Only then Pakistan's promising hydrocarbon potential would be realized.

EVALUATION OF LANDSAT DERIVED EXPLORATION LEADS FOR HYDROCARBON MICROSEEPAGE
USING THE MICROBIAL OIL SURVEY TECHNIQUE, OSAGE COUNTY, OKLAHOMA

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SUMMARY

Exploration leads derived from the integration of Landsat and subsurface geologic data were evaluated using the Microbial Oil Survey Technique (MOST). Areas of significant hydrocarbon microseepage were detected in proximity to some of the exploration leads, and also nearby production.

In 1984, a Landsat study of Osage County, Oklahoma, was carried out by Earthsat Corporation, for the Osage Indian Tribe. Exploration leads identified in this report were selected by Geo-Microbial Technologies, Inc. (GMT), for evaluation using the Microbial Oil Survey Technique. This method detects hydrocarbon microseepage by isolating hydrocarbon indicating microorganisms.

The intent was to identify exploration leads related to high levels of hydrocarbon microseepage. Highgrading leads in this manner reduces the large number of leads and features mappable from satellite images by identifying only those with true significance for hydrocarbon potential. This approach focuses exploration efforts which reduces costs of other exploration methods.

To evaluate the exploration leads a sampling grid was designed for each area, depending on its size. Near surface soil samples were collected on foot at 100 meter spacing along north-south, east-west trending lines. Samples were returned to GMT labs for immediate processing by the MOST method.

A series of dilutions for each sample was made and plate cultures prepared. The data were available in one week. A statistical smoothing function was applied to the data and contour maps were prepared. These maps were then overlain on the photogeologic interpretation of the individual leads. Significant correlation between high levels of microseepage and the Landsat interpretation were then noted. Drilling records were then consulted to determine if any drilling had been carried out on or near these leads and the results. The integration of remote sensor and biogeochemical data in this manner can increase the speed with which significant leads are identified and exploited.

EFFECTIVENESS OF PHOTOGEOLOGIC MAPPING IN
ROCKY MOUNTAIN FORELAND BASINS

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SUMMARY

Photogeology has been utilized as a petroleum exploration tool in the Rocky Mountains for over fifty years. A measure of the value of the tool is to determine the percentage of correlation between photo observed structure and production. During the past 30 years, IntraSearch Inc. has photogeologically mapped most of the Rocky Mountain sedimentary basins using low altitude photographs. To test the effectiveness of the tool, all or parts of fourteen Wyoming intermontane basins, (total production; oil - 5,469,975,247 BLS, gas - 11,222,711,842 MCF) primarily in a foreland tectonic setting covering a 93,000 square mile area, were examined to determine how many areas (oil and/or gas fields) of current (as of 12/31/85) or previous production exhibit surface structural evidence observable on 1:60,000 scale black and white aerial photographs. Three types of anticlinal traps were examined; 1) singly plunging, 2) doubly plunging, and 3) faulted nose.

Forty percent of all oil and gas fields are photogeologically observable. For different basins, this percentage varies from 3 to 30 percent where production is stratigraphically controlled, 70 to 100 percent where production is structurally controlled and 35 to 65 percent in basins with both stratigraphic and structural controls. For each anticlinal type, where there is coincidence with production, the percentage of occurrence varies; singly plunging - 40%, doubly plunging - 50%, and faulted nose - 10%. Sixty percent of all photogeologically observable anticlinal traps occur in non-producing areas and are undrilled or drilled dry.

A comparison of the effectiveness of geologic interpretations between 1:60,000 scale aerial photography and 1:1,000,000 scale Landsat imagery (MSS, black and white, band 7) in the structural trap dominated Big Horn Basin of Wyoming in identifying areas of production, indicate that aerial photography is 65% more effective than Landsat imagery. Twenty-five percent of all discovered fields are observable on Landsat imagery.

Photogeologic evaluation is a cost effective (Landsat - 26 cents/sq. mi.; 1:60,000 - \$4.00/sq. mi.) and successful exploration tool for generating petroleum prospects. Natural color, 1:24,000 scale photography has increased the effectiveness of the tool. In the Rocky Mountains, a mature region of exploration, many known photogeologic prospects remain undrilled and await renewed activity.

UTILIZING SIDE-LOOKING AIRBORNE RADAR (SLAR)
FOR OIL & GAS PROSPECTING IN LOUISIANA

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SUMMARY

Research carried out in the early 1960's demonstrated the value of radar imaging systems for mapping geologic structures, faults, fractures, and other lineaments as well as folds and regional lithology. Its sensitivity to topographic expression and surface roughness made radar imagery an important source of information for both energy and mining exploration activities.

The northern third of Louisiana and west central Mississippi were mapped in July 1988 using a state-of-the-art side-looking airborne radar (SLAR) mapping system called Synthetic Aperture Radar (SAR). The area mapped consists of the Shreveport, LA, and Jackson, MS, 2° topographic quadrangles for over 16,000 mi² of synoptic coverage. The area was flown as part of the U. S. Geological Survey sponsored National Mapping Program.

The SLAR mapping program is particularly useful to the oil and gas industry because of the ability of the SAR system to detect the surface expression of structures that form oil and gas traps in the subsurface. An initial examination of the imagery reveals a number of significant lineaments, most of which were unknown prior to these data. Some correlate with known regional structures while others may represent discontinuous subsurface faults previously thought to exist only at great depths. Other lineaments which have never been observed before criss-cross Louisiana from Texas, Arkansas, and Mississippi.

There are 44 mapped salt domes and surficial domal structures in the area covered by the SAR imagery; the imagery indicates the existence of another 100+ circular anomalies for which no information currently exists. Understanding the nature and extent of the radar lineaments and other anomalies produced on the visual image will provide an evaluation tool that could greatly enhance the detection and location of other potential oil and gas prospects.

There are many applications for which this SAR imagery is aptly suited, but the greatest benefit Louisiana could receive from this mapping program clearly lies in the area of energy. Understanding the correlation between the radar lineaments, circular anomalies, and existing oil & gas fields could contribute substantial knowledge toward identifying additional petroleum reserves and thus improving Louisiana's ailing oil and gas industry.

A CARTOGRAPHIC DOCUMENT INTERPRETATION SYSTEM

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SUMMARY

DataSpan Technology Inc. of Calgary, Alberta and the Alberta Research Council are jointly developing a system that aids in producing interpreted cartographic data suitable for input to a geographic information system (GIS).

Raster data from a variety of sources including remote sensing, scanned maps, and scanned photographs is processed to produce a vector representation of the image. Features such as shorelines, rivers, roads, and (in the case of maps) symbols are extracted and classified. Data from different sources can be merged and registered before being output in a form suitable for further processing or inclusion in a spatial database or GIS.

The system employs several advanced techniques. Distributed processing takes advantage of a network of workstations to solve problems associated with the massive volume of data which must be interpreted. Artificial intelligence techniques aid in the efficient interpretation of locally ambiguous data which has a unique global interpretation. Classification of highly structured symbols, such as alphanumeric characters, is aided by syntactic pattern recognition techniques.

The system augments and will ultimately replace the current operator-intensive methods of data classification and map interpretation. Presently, the system can quickly carry out many of the tedious tasks associated with data integration. This system is being developed in C++ on Sun workstations at DataSpan Technology and is being used in a production environment to process large cartographic documents.

REGIONAL TECTONICS OF MYANMAR (BURMA) AND ADJACENT AREAS

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SUMMARY

Analysis of 38 contiguous Landsat Multispectral Scanner scenes acquired over Myanmar (Burma) reveals previously unidentified NE-SW trending discontinuities, important extensions of previously mapped fault trends, and numerous structural features that appear favorable for petroleum exploration. A mosaic of these scenes at 1:1,000,000 scale shows all of the N-S trending tectonic elements in detail and in context. Significant right lateral displacement previously postulated along the western India/Asia plate margin is supported by changes in fold trends and antithetic left lateral fault offsets. Integrating the satellite data with available subsurface data has led to a better understanding of subsurface relationships important to hydrocarbon exploration in this historically old but frontier province.

USE OF THEMATIC MAPPER DATA FOR THE DETECTION OF
GOLD BEARING FORMATIONS IN THE EASTERN DESERT OF EGYPT

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SUMMARY

1. OBJECTIVES

Remote Sensing in arid areas experienced a revolutionary development in the last decade, especially since the launch of Landsat-TM. The short wave infrared channels of TM comprise a large amount of spectral signatures in a certain range of the electromagnetic spectrum, which are diagnostic for different mineralogical compositions. Therefore, TM-data are particularly predestinated to detect anomalies in the spectral response caused by mineral changes and alterations. In terms of exploration geology, these anomalies could be secondary indicators for mineral concentrations. In this context, two ancient, now abandoned gold mines in the Eastern Desert of Egypt were mapped by interpretation of TM-images and their lithological setting will be discussed for further exploration in the Eastern Desert.

2. GEOLOGICAL INTRODUCTION

The area under investigation is part of the Egyptian basement complex in the Eastern Desert of Egypt. The Basement belongs to the Nubian Shield, which formed a continuous part with the Arabian Shield before the opening of the Red Sea less than 30 ma ago. The Basement is characterized by volcano-sedimentary rocks, metamorphites, and plutonites of precambrian age. Since pharaonic times, gold mining in Egypt and N-Sudan is well known. All gold deposits in the Eastern Desert are of hydrothermal quartz vein type and disseminations in the wall rocks are not infrequent. A spatial relationship of the gold mineralisation and the host rocks with various country rocks can always be observed. Two gold mining areas, typical for the Eastern Desert of Egypt, will be discussed: Atalla gold mine and El Sid gold mine, situated in the western part of the Central Eastern Desert in the vicinity of the Quft-Qusier road. Both localities are part of a mega shear zone. At Atalla mine, the gold bearing quartz veins occur in a alkali-feldspar granite, in contact to metavolcanics and a small serpentinite lense, covered by rhyolites and tuffs. The quartz veins at El Sid mine are located in metabasalts, serpentinites, and granitapophyses. The country rocks are built up by a monzogranite, acidic volcanics, and clastic sediments, intersliced along thrust and shear zones.

3. METHODOLOGY

On base of spectral measurements of rock samples with a laboratory spectrometer (Lambda 9/Perkin-Elmer), the spectral properties of the main rock units in the test area were determined. The most useful combination for exploration geology in the Eastern Desert was TM-bands 4, 5, and 7 colour coded as Blue, Green, and Red. To decorrelate the data by changing the spectral and structural information simultaneously without enhancing the original hue, an Intensity-Hue-Saturation transformation in the colour space was applied as well as conventional contrast and edge enhancements. Band ratioing techniques are able to emphasize the spectral differences between different surfaces. Therefore, ratios were chosen as additional information to identify properly different metavolcanics and serpentinites.

4. RESULTS

First, results of the interpretation on base of a decorrelated 1, 4, 7 TM-image is a geological map at a scale of 1:100,000. The regional interpretation was controlled by ground checks. After additional investigations on ground check data and spectral measurements, as well as geochemic and petrographic studies, a concept for the verification of the Thematic Mapper data for gold exploration in the Eastern Desert of Egypt could be elaborated. The relationship of the gold occurrences with their lithological and tectonic setting and their typical spectral features are demonstrated in detailed maps.

CORRELATION IMAGES OF DH₂O & DCO₂
AND THEIR SIGNIFICANCE IN GOLD EXPLORATION

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SUMMARY

It is known that the hydrothermal gold deposits associates with lots of H₂O (liquor or vapour) and CO₂ in the course of formation. The relative amount of H₂O and CO₂ can be revealed by measuring the infrared optical density of H₂O and CO₂ in the inclusions of quartz (as DH₂O and DCO₂). Recently in China, DCO₂ and DH₂O have been used to evaluate gold deposits of quartz-vein type, while used to identify the depth of ore deposits (Liu Benli, 1987).

H₂O and CO₂ are the most active components of thermal-liquid system with strong permeability, large function range, and relatively uniform distribution. When their concentrations are high enough, they may escape from the thermal liquid and cause metasomatism to the adjoining rocks (mineral variation) while defuse along fussions and pore spaces. Consequently, when weathered, the eluvium or the soil of mineralized area may be abnormal in chemistry components and texture. These anomaly of components and texture usually form a desperse halo. We found that it can be detected by remote sensing sensors while it cannot be easily identified by naked eyes and ordinary petrology work. Through specific transformation of the TM data, we have obtained the correlation images (abbreviated to C-images) of DH₂O and DCO₂, and outlined the distribution and characteristics of the desperse halo. In two subareas, it proves to be beneficial that by this method we have well located the probable sites of gold enrichment through computer processing of C-images of DH₂O and DCO₂ and TM images of certain band. The main points are as follows.

(1) Creation of the C-images of DCO₂ and DH₂O. Because DCO₂ and DH₂O in the inclusions of quartz closely correlate with the desperse halo in the ground, it is possible to formulate a statistical model (transformation equations) out of the value of DCO₂ and DH₂O and the spectrum characteristics of the desperse halo. According to the equations, and by digital image processing system, we can obtain the optical density correlation images whose brightness value presents value of DCO₂ and DH₂O in unknown area. Obviously, transformation equation of H₂O is different from that of CO₂. Additionally, due to the difference of adjoining rocks, the density of structure fragmenting, and the climate zone, it is obvious that metasomatism strength by H₂O and CO₂, newly generated minerals, eluvium of bed rock, desperse halo in soil all varies a lot; so different transformation equations are required in different places corresponding to the actual situations.

(2) Extraction of Gold Information and Its Application Effect. Two subareas (Xiaxyiing, Dongmao) are well researched using TM tape (26 April 1987). There are similar geological

conditions (widely exposed bed rocks, moderate structure fragmenting; most weathering products are eluvium and thin solum, vegetation is mainly developed on the rear slopes) in the two sub-areas. Using the same transformation equation in two areas, we have obtained the respective C-images, and correlation coefficients of brightness value with DCO₂ and DH₂O are larger than 0.9.

In order to obtain good effects of gold information extraction, the first step is to determine the brightness value range of the C-images relevant to gold enrichment and to compress that unrelevant to gold enrichment; and then to process the images with different projects of color combination. Xiaxyiing subarea: assign red to C-image of DCO₂, green to C-image of DH₂O, blue to TM 5/7; Dongmao subarea: red to C-image of DCO₂, green to C-image of DH₂O, and blue to TM5.

After color combination, on the image of Xiaxyiing subarea, apricot yellow indicates higher DCO₂ in rocks than the critical DCO₂ value of gold enrichment and relatively high DH₂O, which accords with the mineralization conditions while no obvious corrosion developed on the surface. This means there may be blind ore deposits in depth. On the same image, fuchsin indicates higher DCO₂ and lower DH₂O, in which case corrosion is well developed on the ground and gold enrichment is probable. Apricot yellow and fuchsin are characteristic tones of gold mineralization indicating the prospected target areas. Green on the image means higher DCO₂, lower DH₂O, and not developed corrosion, which indicates the tailings halo without exploration value even though there is ground mineralization. After interpretation, there are five sites corresponding to the characteristic tones and there are corrosion and mineralization in each of the sites, one of which has been exploited.

On the processed image of Dongmao subarea, light bright apricot is the indicator of probable gold enrichment. Three prospected target areas are interpreted and also confirmed by field work, in one of which there is a rich ore bed that has been exploited by the county.

ENHANCEMENT OF LANDSAT THEMATIC MAPPER IMAGERY
FOR RESIDUAL SOIL MAPPING IN THE SW MINAS GERAIS STATE, BRAZIL:
A PROSPECTING CASE HISTORY IN GREENSTONE BELT TERRAIN

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SUMMARY

The use of remote sensing for mineral exploration in south-central Brazil is constrained by the virtual absence of exposed bedrock. The region has been subject to deep weathering, which has produced a thick blanket of residual soils. These soils support a flora of natural woodland, open savannah scrub, coffee plantations, and grass for livestock grazing.

Digital image enhancement has been used to identify and separate iron-rich soils derived from basic and ultra-basic metavolcanics from soils in areas of migmatitic gneiss and other rock types. The second objective of the study was to locate areas containing anomalous iron mineral concentrations, in soils derived from weathered sulphide ore bodies.

The study is based on 15 x 15 km sub-scene, containing the O'Toole nickel sulphide orebody, located in reworked Archaean meta-komatiites and basalts near the village of Fortaleza de Minas. The gossan rich soils associated with the deposit have been used as a 'training' locality for spectral enhancement of iron oxide (limonite) minerals using TM images.

The most successful image processing techniques for iron-rich soil and gossan mapping in the test area are band difference, decorrelation stretch, and four dimensional display of selected principal components. Some discrimination has been achieved between terra-rossa soils, weathered from limestone and marble lenses, and soils derived from basic igneous rocks. The refined enhancement techniques for gossan prospecting are applicable, regionally, to a larger area and potentially to areas of south-central Brazil with similar geological, climatic, and pedological characteristics.

EXPLORING FOR TIN AND TUNGSTEN IN SÃO PAULO STATE, BRAZIL,
WITH AN INTEGRATED PROGRAM OF REMOTE SENSING AND GEOLOGY

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SUMMARY

An interactive methodology using remote sensing and geologic data was applied to search SN-W prospective targets in the Southeastern São Paulo State, Brazil.

The investigated area has an extension of 32,000 sq. km. By road, the access is very difficult due to rough relief, dense forest cover, tropical climate conditions, and rock outcrops are scarce. The remote sensing approach was fundamental in this scenery, with cost-time advantages compared with geochemical prospection and geological systematic survey.

The lithological framework consists of high to low grade metamorphic assemblages, including varied orthogneisses and metavolcano-sedimentary supracrustals, intruded by granitoid stocks and batholiths. Some small SN-W occurrences were taken as test sites. They are: (1) SN-W bearing greisens, and (2) skarn concentrations in roof pendants.

The steps followed were: (1) detailed statistical investigation of lineaments from Landsat and Radar imagery, which resulted in maps of frequency, density, azimuth mean deviation, atypicality angular index, and maximum fracturing axis; (2) drainage analysis, with definition of morpho-structural anomalies resembling that of the test sites; (3) compilation of geologic data, with definition of tectonic domains and enhancing features which may represent post-orogenic or anorogenic granitoid intrusives or cupolas; (4) analysis of Landsat TM-5 images, with definition of homologous areas, structural patterns, etc.

The thematic maps obtained allowed to recognizing patterns, trends, and regional controls of granitic intrusions and led to delimit a lot of favourable areas. Airborne radiometric data for U, Th, and K, and available geochemical information were taken into account to select the best targets. More than 100 areas were indicated and 30 are now being under consideration for more

detailed investigation. Preliminary field work on three areas showed a wide occurrence of greisens in one of them.

QUANTITATIVE LITHOLOGIC MAPPING OF HYDROTHERMALLY ALTERED
VOLCANIC TERRAIN IN SPECTRAL RATIO FEATURE SPACE:
AURORA MINING DISTRICT, MINERAL COUNTY, NEVADA

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SUMMARY

Methods for lithologic mapping with remote sensing techniques were sought which could generate results that are quantitative and transferable from site to site and time to time. Spectral ratio feature space was chosen as a framework within which various lithologies would be plotted to determine repeatable distributions and relationships. Laboratory-derived spectral data were plotted using ratios of wavelengths corresponding to the mean wavelengths of Landsat Thematic Mapper channels: $0.66\ \mu\text{m}/0.485\ \mu\text{m}$ vs. $1.65\ \mu\text{m}/2.22\ \mu\text{m}$. Spectra of a diverse set of 62 minerals and rocks were plotted as a function of these ratios. Distinct two-dimensional distributions were found that provide a sound basis for lithologic clustering in terms of three spectrally-dominating molecules: silica (SiO_2), iron-iron oxide (Fe , FeO), and hydroxyl or free water molecule (OH , H_2O).

Field radiometer data and radiometrically/atmospherically corrected Thematic Mapper reflectance data of the Aurora Au/Ag mining district were then plotted using the same spectral ratios (TM 3/TM 1, TM 5/TM 7, TM 4/TM 5). The observed lithologic distributions were found to be similar to those of the laboratory spectra. Two-ratio plots of the TM 3/TM 1 vs. TM 5/TM 7 combination using spectral classes generated by an unsupervised classification of the three ratio-enhanced images were used in conjunction with TM 3 vs. TM 1 two-channel plots to produce detailed lithologic image maps of the study area. Two-ratio plots of the TM 4/TM 5 vs. TM 5/TM 7 combination proved useful in discriminating pixels of pure rock and soil from those contaminated by vegetation.

The above image processing method was successful in delineating argillic and phyllic hydrothermal alteration zones in semi-arid terrain underlain by Tertiary intermediate to felsic volcanic rocks. The method can be quantitatively applied to other terrains as long as radiometrically calibrated and atmospherically corrected Thematic Mapper data are used.

PHOSPHORITE EXPLORATION IN THE THANIYAT AND SANAM DISTRICTS,
KINGDOM OF SAUDI ARABIA, USING LANDSAT THEMATIC MAPPER DATA

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SUMMARY

Two phosphorite zones of Late Cretaceous-early Tertiary age were mapped (by Meissner and Ankary in 1971) within a sedimentary rock sequence in the Thaniyat district in northwestern Saudi Arabia. The nearly horizontal sequence is exposed along dominantly south-facing scarps. It consists, from bottom to top, of a sandstone bed, a dolomitic limestone bed (Late Cretaceous age), a phosphorite zone of uneven thickness that ranges from 1 m to 5 m, a chert layer, and a massive bed of hematite-stained, crystalline limestone containing a thin (less than 1 m) zone of phosphorite. The P_2O_5 content of both phosphorite zones averages about 20 wt %. The upper limestone forms resistant ledges and mesas. Most scarps are covered by talus derived from either the upper limestone or the lower phosphorite zone. The surrounding area is desert pavement. Both the desert pavement and the upper limestone are covered to various degrees by a lag of brown to black chert pebbles.

Field reconnaissance on February 6, 1988, by Farasani and Dini in the Sanam district (adjacent to the Thaniyat district on the southwest) resulted in discovery of a bed of phosphorite 3.5 m thick in the upper part of the walls of a large graben; the phosphorite contains about 20 wt % P_2O_5 . This discovery led to our Landsat Thematic Mapper (TM) study of both districts to determine if TM data could discriminate the known phosphorite deposits at Thaniyat and, if so, if these data could be used to help discover additional phosphorite deposits in the Sanam district.

Statistical and visual analyses performed on the Landsat TM data from Thaniyat indicate that certain combinations of these TM band ratios best discriminate the mapped phosphorite in the Thaniyat district. These TM band ratios include TM 1/TM 4 (or TM 1/TM 3), TM 3/TM 4, and TM 3/TM 7 (or TM 5/TM 7). Our results indicate that absorptions in the near and middle infrared spectral regions are important factors in this discrimination. With these band-ratio images, we could map the distribution of the lower sandstone (both the varnished and unvarnished exposures), of the upper limestone (whether densely or lightly covered with chert), of the surrounding desert pavement, and of units that correspond to the mapped phosphorite deposits. Because the exposures of phosphorite on the talus-covered scarps are small and scattered, it is difficult to determine whether the band-ratio images are discriminating the phosphorite exposures and their talus or the fresh limestone exposures and their talus. We are still examining the TM-band data and the chemical and mineralogical data of selected sample sites to determine if subtle color changes in the band-ratio images represent phosphorite or fresh limestone exposures or both. Even if the phosphorite cannot be discriminated, we believe that the band-ratio images can be a reconnaissance tool for its deposits in the adjacent Sanam district: here the phosphorite is underlain by sandstone and overlain by chert, both of which are discriminated in the Thaniyat district.

We prepared similar TM band-ratio images for the Sanam district that show the distribution of the exposed sandstone, the desert pavement, and a bed covered by chert pebbles. Field reconnaissance using these band-ratio images determined that the bed covered by chert pebbles is a phosphorite zone of considerable areal extent, which trenching showed to average 7 m in thickness. This new phosphate rock resource is estimated to total 70 million tons.

MINERAL EXPLORATION IN THE YEMEN ARAB REPUBLIC BY USE OF TM-DATA

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SUMMARY

Investigations have been carried out at two different locations in the Yemen Arab Republic to trace the relationship between diagnostic signals received from Landsat - Thematic Mapper (TM) data and mineralized ground districts. To meet the objectives, an IHS-decorrelation process involving bands 1, 4, and 7 (coded blue, green, and red) was used to enhance diagnostic features associated with hydrothermally altered areas. This concept facilitates excellent overall rock discrimination and provides the possibility to enhance the signal for the presence of iron oxides (red), clay minerals, and magnesite (cyan). Variations in signal will be explained by lab-spectrophotometry and XRD-analyses.

CASE STUDIES

Sadah Area

The area north of Sadah is mainly built up of Precambrian metamorphic rocks of the Arabian shield. These are mainly metasediments and metavolcanic rocks intruded by pre-tectonic to late tectonic granites to granodiorites. The grade of metamorphism corresponds with the greenschist to amphibolite facies. The basement is overlain by fluvial delta sediments (sandstones and conglomerates) of the Wajid Sandstone to Ordovician to Permian age.

Cyan colors are displayed by altered quartz eye porphyries containing some kaolinite and which are characterized by Au occurrences. Additionally, this specific color is displayed by altered dolomites due to magnesite content that are associated with all gossans in this area. Dolomites that are not associated with gossans do not display cyan colors because of missing compounds of magnesite. The gossans itself do not display the typical red color (by using the described concept) according to limonitic rocks, as Fe^{2+} , $3+$ is not disseminated.

Anomalous red colors are exhibited by Fe-bearing layers of the Wajid sandstone and by altered greenschists that are indicative for Au occurrences in quartz veins. The latter anomalies indicated the location of ancient gold mines recently rediscovered by French geologists.

Wadi Nuni Area

The Wadi Nuni/Wadi Mujib area is located southwest of Sadah close to the Red Sea graben. It is mainly built up by sequences of greenschists and muscovite, chlorite schists intercalated by serpentinite and talc schists, and surrounded by aplite granites and migmatites.

Parts of the schistose complex are slightly bleached due to hydrothermal alteration. The N-S elongated anomaly, hardly visible in field is strongly enhanced by the color composite. It is displayed in bright tones to cyan colors according to magnesite and pyrophyllite.

Analyses of profiling and stream sampling yielded an anomalous high content of chromium/nickel throughout the altered area. This anomaly was newly discovered and demonstrates impressively the potential of remote sensing techniques for exploration purposes.

INTEGRATED MINERAL EXPLORATION IN NORTHERN MEXICO
USING LANDSAT, AERIAL PHOTOGRAPHY, AND GROUND WORK

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SUMMARY

Gold, silver, and copper have been mined from Placer de Guadalupe in Northern Mexico since the colonial time. The area is remote and rugged, and even after three centuries of ore exploitation, the geologic structure remains poorly understood. Ore production has been less than optimal and much resources have been wasted because of the lack of understanding of the geologic framework.

The Placer the Guadalupe area is formed by a thick sequence of structurally complex Paleozoic and Mesozoic sedimentary rocks, mostly marine in origin. Tectonically, it corresponds to the southern edge of the North American Craton for the late Paleozoic, to the Mexican Caa during the Mesozoic, and to the easternmost reaches of the tertiary Mexican volcanism.

Original photogeologic and field work during the 60's yielded the only geologic model available for the area. This concept was reviewed based on the analysis of Landsat imagery. Resulting new hypothesis were tested in the field producing an accurate and detailed geologic map at 1:50,000 scale.

The spectral resolution of Landsat Thematic Mapper brought about relevant and unique information for mineral prospection. Using digital data, local events were examined in relation to the regional geology, enabling us to predict new mineralizations. Previously unsuspected mineral deposits were located. Possible ground water sources were identified. A cost analysis is also discussed.

REMOTE SENSING AND DATA INTEGRATION FOR TARGETING
STRATABOUND GOLD MINERALIZATION IN GLACIATED TERRAIN:
A CASE STUDY FROM ATIKOKAN AREA, ONTARIO, CANADA

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SUMMARY

The application of new techniques in mineral exploration (here remote sensing and data integration) has been done in the Atikokan area on a large property owned by Mimiska Inc.

General geology consists of metavolcanic rocks structurally controlled by the Quetico fracturation system at the south and the Steeprock lake fracturation system at the east. South of the Quetico fault are metasediments and north of metavolcanics is a granitic batholith. Major parts of the area is overlain by glacial deposits, such as lodgement till, glacio-fluviatile and glacio-lacustrine deposits.

Remote sensing has been done regionally (1:100,000) and locally (1:24,000) using Landsat-TM-5 data. At regional scale (TM quadrant), five structural domains were delimited. At local scale, lineaments were classified by means of their geographical extent (regional and local) and their degree of importance (first and second order).

They were grouped into families of same direction and geological interpretation has been conducted considering the structural domain and the classification criteria for giving a clear geological significance to lineaments.

Humus geochemistry and geophysics has been done on selected parts of the property, e.g. the metavolcanics north of the Quetico fracturation system and part of the batholith.

Data integration has been carried on using remote sensed lineaments, geochemical and geophysical data. Multivariate statistical processing has been used to derive a good empirical and theoretical gold mineralization model and high priority drilling targets. Significant economic gold mineralization has been intersected using this technique.

Remote sensing and data integration proved to be a valuable tool for targeting gold mineralization and should be used and adopted in mineral exploration programs in similar terrains.

LANDSAT LINEAMENT AND MAGNETICS A GUIDE TO AU AND PRECIOUS METALS
EXPLORATION IN MOHAVE, LA PAZ, AND MARICOPA COUNTIES, WESTERN ARIZONA

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SUMMARY

This paper addresses

1. Landsat Lineament analyses and integration with magnetic and gravity data as a geological exploration tool within Au and precious metals mineralized terrain in the Archean-Proterozoic Mohave segment in Western Arizona.
2. Technology transfer and data correlation from 1:100,000 regional to detailed airphoto scale to groundtruthing of vein controls at Au and precious metals prospects and establishing guidelines for exploration follow-up.

Northwestern Arizona and adjoining lands in Southern Nevada and Southeastern California contain Precambrian greenstone belt terrains which were caught in Cretaceous - Tertiary Basin and Range extensional tectonics and Laramide intrusive activity. The effects of reworking is illustrated by Au and precious metals prospects in perfect volcanogenic, interface-hosted setting, and Au mineralized vein systems arranged along N20W Basin and Range trends.

A large scale Landsat TM and airphoto lineament study combined with N.U.R.E. vertical gradient regional magnetic data and focusing on reworked Precambrian fault tectonics was undertaken in order to unravel metallogenic patterns and define regional and detailed controls of Au and precious metals prospects.

Exploration Highlights

1. N30E Precambrian trends parallel to and along the Hurricane and Grand Wash Fault systems extend from the Colorado Plateau SSE through Western Arizona and into detachment faulted terrains in Maricopa and La Paz Counties to the Mexican Border and illustrate a Precambrian backbone structure in Southwestern United States.
2. A fundamental alignment of Laramide granitoid intrusives, Tertiary volcanic centers including breccia pipes together with a hard minerals spectrum of Au and precious metals vein, volcanogenic massive sulphide deposits and iron formations of Precambrian age, complex polymetallic vein and Cu-Mo prospects of Laramide age exists along the N30E trend and indicate reactivation of Precambrian fault systems.
3. Detailed prospect work in several Au and precious metals camps reveal the importance of conjugate fault tectonics with N30E and N20W as fundamental vein controls.

4. Other major structural trends are (a) a conjugate N70E and N80W system combining a reworked ENE-WSW Precambrian fault trend subparallel to the Tertiary Gairlock Fault and a Las Vegas Shear-Walker Lake-Texas Lineament-related fault system.

Conclusions

- The study opens up new exploration avenues for large tonnage heap-leach Au and precious metals deposits in Southwestern United States.
- The combined Landsat-airphoto and potential field geophysics interpretation technique with its versatility in work scale is a powerful tool to eye-balling structure in complex overprinted terrains.

EXAMINATION OF SELECTED SATELLITE AND AIRBORNE REMOTE SENSING SYSTEMS
FOR GEOLOGIC MAPPING AND MINERAL EXPLORATION IN SEMI-ARID TERRAINS

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SUMMARY

Satellite and airborne remotely sensed data are valuable and often underutilized tools for geologic mapping and mineral exploration, especially in semi-arid terrains where rocks are well exposed. This paper illustrates improvements in geologic remote-sensing capabilities, particularly as relate to lithologic mapping and compositional determinations, that have resulted from advancements in sensor technology. Data from six different satellite and airborne remote sensing systems that record reflected and emitted electromagnetic radiation in the visible through the thermal infrared portions of the spectrum were acquired over the same geologic test site in Utah. Attempts have been made to evaluate and document the geologic information content of these various data and to develop data products that best display the information present.

The central Drum Mountains, located in west-central Utah, were selected as the field site for these studies because a variety of rock types are well exposed there in a physiographic setting typical of the semi-arid western United States. Rocks exposed in the study area include a sequence of limestones, dolomites, and shales that overlies quartzite and argillite. Silicic, intermediate, and mafic volcanic rocks occur in contact with sedimentary units throughout the area. The volcanic rocks have been hydrothermally altered in places, and some adjacent carbonate rocks have been bleached and recrystallized. A contact metamorphic aureole in the central part of the area is characterized by carbonate bleaching and development of calc-silicate mineralization in limestone and shale units. The aureole is associated with the intrusion of two small stocks, one of which is a fresh diorite and the other a mineralized and intense hydrothermally altered monzonite porphyry.

Initial remote-sensing studies of this area focused on comparing capabilities of Landsat multispectral scanner (MSS) and thematic mapper (TM) data to detect hydrothermally altered rocks and to discriminate different lithologic units present in the field area. Simultaneously acquired MSS and TM data were digitally enhanced using band ratioing, principal components analysis, and other techniques. Analysis and interpretation of images produced by these techniques demonstrate that TM data provide a significantly greater amount of useful geologic information compared with MSS data, particularly for detecting hydrothermally altered rocks and

for discriminating different rock units exposed in the field area. A map of hydrothermally altered rocks interpreted from TM data accurately portrays the occurrence of all known exposures of such rocks in the area, but does contain certain errors of commission where unaltered rocks containing significant concentrations of Fe-oxide minerals and hydroxyl-bearing or recrystallized carbonate minerals appear similar to altered rocks on the TM images. A geologic interpretation of the field area based on TM data compares favorably, in detail and accuracy, with the 1:250,000 scale U.S. Geological Survey geologic map of the area.

Images produced from multispectral Satellite Pour l'Observation de la Terre (SPOT) data proved less useful, because of their more limited spectral coverage, than TM data for detecting hydrothermally altered rocks and differentiating lithologic units in the Drum Mountains. However, panchromatic SPOT data were usefully applied to improve the detail of TM-based interpretations. By digitally merging SPOT panchromatic data with various enhanced TM images, new images were created that capture most of the spectrally defined compositional information in TM data, but at 10 m spatial resolution. Furthermore, when the enhanced TM images are merged with the second image of the SPOT panchromatic stereo pair, rather spectacular, high-spatial-resolution, false-color stereo images are produced, and these provide very useful for interpreting all aspects of the field site geology.

Six-band, 20 m spatial resolution Thermal Infrared Multispectral Scanner (TIMS) data acquired over the Drum Mountains were evaluated to determine their capabilities to differentiate rock types exposed in the field area, particularly various silicate rocks which typically have similar reflectance characteristics in the wavelength regions covered by TM but which vary in their thermal emittance spectra. Due to influences of surface temperature, TIMS data are often highly correlated among bands. Consequently, to best display variations in thermal emittance related to compositional differences, Drum Mountains TIMS data were digitally enhanced using a decorrelation stretch technique. The resultant images provided excellent separation of the three major rock sequences in the field area - quartzites, volcanics, and carbonates. However, differentiation of lithologies within these groups was not better than the discrimination provided by TM data.

The Airborne Visible and Infrared Imaging Spectrometer (AVIRIS) is an experimental airborne sensor developed by NASA as a prototype to the High Resolution Imaging Spectrometer (HIRIS) which is planned for deployment on the Space Station's first polar orbiting platform in the mid-1990's. AVIRIS records reflected solar radiation in 220 contiguous spectral bands between 0.4 and 2.45 μm at 20 m spatial resolution, thus providing a detailed spectrum for each 20 m x 20 m ground pixel imaged. The implications of this capability for the remote identification of rocks and minerals are significant.

AVIRIS data acquired over the Drum Mountains unfortunately were characterized by a low signal-to-noise ratio in the 1.85 to 2.45 μm region, thereby inhibiting evaluation of the utility of AVIRIS data for geologic studies in semi-arid terrains. Band averaging was applied to the data to compensate for signal-to-noise problems, yet resultant images were less useful than enhanced TM images for lithologic discrimination.

More success in the analysis of AVIRIS data was achieved by digitally matching AVIRIS image spectra with laboratory spectra of known minerals and with spectra measured in the field using a portable field spectrometer. Spectral Analysis Manager (SPAM) software was used to

search the image and alarm pixels having spectra that match a reference spectra within defined threshold values. The result was a thematic display of pixels that, in a general sense, could be interpreted as being comprised of rocks and soils with contents high in the reference mineral, for example, kaolinite. Mismatches were common due, at least in part, to the signal-to-noise problem, yet significant correlations with ground data verify the potential for applying these techniques with greater success when improved AVIRIS data become available.

Capabilities to interpret geologic information from remotely sensed data have improved significantly since the launch of Landsat 1 as a result of advancements in sensor technology. Sensor spectral characteristics and spatial resolution are the variables which most dictate the types and amounts of geologic information available from the data. More comprehensive interpretations typically result from the application of multiple sensors and from combining unique attributes of their data in the interpretation process. Sensor evaluation studies in the semi-arid and geologically diverse Drum Mountains will continue with evaluation of a second AVIRIS data set, 24-channel Geoscan MKII airborne multispectral scanner data, and GER 63-channel airborne scanner data, all of which are scheduled for acquisition in the summer of 1989.

COMBINED LANDSAT IMAGERY AND RASTER BASED GEOPHYSICS AS AN EXPLORATION TOOL

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SUMMARY

We investigate the utility of combined satellite imagery and raster based geological and geophysical data sets for mineral exploration in the Abitibi region of Quebec.

The problem of extracting geologic information from satellite images in a vegetated, and formerly glaciated terrane for purposes related to mineral exploration is approached empirically by compiling a database of coregistered Landsat TM imagery, aeromagnetics, gravity, topography, mine and mineralization locations, and outcrop lithology. Unlike digital contour compilations that merely permit the user to access and overlay "geoinformation" in selected areas, the raster format presents the data as brightness maps, emphasizing amplitude variations rather than gradients. Standard image processing techniques and image statistical analyses may be applied directly to determine correlations between TM band brightness, geophysics, and known lithology. The most effective enhancement methods and "band" combinations for lithological discrimination and structural interpretation can then be used to perform automated mapping in similar terranes and, it is hoped, to select exploration targets on the basis of similarities between productive and unexplored areas.

Due to the diverse formats of the original data, a number of difficulties had to be overcome in reducing them to a common base. Outcrop lithology is digitized from hand-colored maps with an Eikonix digitizing camera and then converted to classified pixels (regions of interest) using an IIS System 600 image processor. Irregularly spaced gravity measurements are interpolated using a Fortran 77 based implementation of Shepard's (1968) algorithm that is sensitive to the density of data within the interpolation window and thus avoids spurious interpolations. A variation of this method is developed to interpolate contoured data, specifically topography, digitized using a Summagraphics digitizing table and adapted software.

An assessment is made of the advantages of the synoptic view and raster based presentation of geophysical data over more traditional formats for mineral exploration efforts in the Abitibi region near Noranda, Quebec. This well explored area presents an extensive information base with which to test target evaluation methods. The raster base permits automated extraction of new data aspects, for example, magnetic gradients, topographic roughness, or regional brightness

variations of specific outcrop types. Selected areas are used to refine supervised classification methods which can then be tested in other equally well mapped areas. Subclasses of training sets may be defined on the basis of local or regional variations. Overlay of the original data points on interpolated images and blanking in unsampled areas helps to over intepretation.

INTEGRATED REMOTE SENSING/VECTOR-BASED GIS TECHNOLOGY FOR
GOLD EXPLORATION, ROUND MOUNTAIN DISTRICT, NEVADA

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SUMMARY

A microcomputer-based image processing/geographic information system (GIS) was employed to coregister and analyze multiple data sets from Landsat Thematic Mapper (TM) imagery and published geological and geochemical studies of the Round Mountain, Nevada 7.5 minute quadrangle. This investigation was undertaken to determine if favorable patterns of mineralization analogous to the Round Mountain gold deposit could be delineated by combining available field data with new information gleaned from multispectral TM imagery.

The remotely sensed, geochemical, and geological characteristics of the Round Mountain gold deposit provided a model within which the entire study area could be evaluated. Vector data sets were digitized from maps as points (e.g., historic mines and prospects), lines (e.g., faults, dikes, streams, roads), and polygons (e.g., geologic rock units, geochemical anomalies) and were compiled with attribute data in a GIS database. The TM imagery was processed to enhance alteration features related to mineralization and linear features indicative of fracturing and faulting. To detect the presence of iron and clay, an Intensity, Hue, Saturation transformation was applied to band ratios of the TM spectral data. The resultant image was also analyzed by supervised and unsupervised classification methods to extract a spectral signature for the mine area.

The registration of these various data sets in a raster format enabled the cross-correlation of multiple data layers. A data reduction procedure was used to apply the model to the database interactively on a color RGB monitor. The results produced some interesting relationships, and delineated several favorable exploration areas. Furthermore, the GIS derived prospects provided a means of verifying a computer generated spectral signature for the Round Mountain deposit. More field work is necessary to substantiate these findings.

MICRO-BASED SPATIAL ANALYSIS FOR GEOLOGICAL MAPPING AND MINERAL EXPLORATION

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SUMMARY

Geological maps of many kinds portray selected geological facts in their correct spatial relationships. In preparing such maps, field geologists have long used four guiding imperatives:

- (1) select facts that are relevant to the specific theme;
- (2) separate geological fact from inference;
- (3) instill confidence with converging lines of evidence; and,
- (4) use multiple hypotheses to advance understanding

Though subjective, these principles are cost-effective and valid guides for digital mapping of geology.

Our fifteen years of experience with cerebral processing of multiple sets of data has now been adapted with SPANS* software to produce digital synergistic interpretive geological (SIG) maps. The first test of such digital mapping is reported here for an area near Halifax, Nova Scotia. This test demonstrates the ability of SPANS to quickly overlay, correlate, model, and predict using both digital and analog databases. The analog data are input through the PROCOM** system with digitizing tablet.

An expert field geologist stratifies and compresses the input data while retaining geological significance. Such compression has two principal advantages: (1) the mapper becomes familiar with each set of data, and (2) the volume of data is reduced dramatically (10^{-4} and 10^{-5} for the quadtree map file). The mapping database of 26 digital files was compiled from 35 different thematic maps and images at diverse scales (e.g. aeromagnetic maps, gamma-ray spectrometer maps, geologic and topographic maps, Landsat MSS and TM images).

The Indexing Overlay Analysis (IOA) capability of SPANS is used to develop and extend quantifiable geophysical signatures for each rock unit. Seven basic steps are followed in producing the final SIG maps: (1) preparation of a digital geological calibration map for known outcrops, (2) development of geophysical correlation maps, (3) development of correlation

* SPANS, SPatial ANalysis System is a menu-driven GIS developed by Tydac Technologies Inc., Ottawa, K1Z 8R7, Canada.

** PROCOM is an optical transfer device with modular add-ons for digitization, stereo-viewing, and change detection. All are products of Gregory Geoscience Limited.

statistics, (4) development of weighting factors for each rock unit, (5) calculation of composite scores, (6) development of indexing overlay maps, and (7) manual editing (e.g. bridging holes in classifications, interpreting geophysical ambiguities, adding strike and dip, etc.)

Initial results suggest that IOA mapping produces a useful preliminary map for field use, especially for rocks similar to the folded Goldenville quartzites and Halifax slates. The digital SIG map also subdivided the Halifax and separated three different Devonian granites. By using expert knowledge, the method can be used to forecast potential for mineral exploration relative to given assumptions. On the other hand, IOA mapping provides little information (other than linear features) for the flat-lying Carboniferous sedimentary rocks. Further work is required to determine whether more geophysical detail and/or other data will improve classification of those rocks. While digital SIG maps have not yet been produced as commercial products, previous experience with other themes suggests that cost reductions will be attained here also.

**FURTHER DEVELOPMENT AND APPLICATION OF GIS TECHNOLOGY AND GEOSTATISTICS
TO ASSIST IN THE EXPLORATION FOR URANIUM IN WESTERN NORTH AMERICA**

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SUMMARY

Microcomputer technology and software have been applied in a multidisciplinary approach to uranium exploration in a study area in the Northern Rocky Mountain Physiographic Province. The study area is about 16,800 square kilometers in size and includes parts of north-eastern Washington, northern Idaho, and north-western Montana states.

Some of the advantages and disadvantages of employing GIS technology for multidata set manipulation are evaluated in this study. The problem of varying intrinsic data resolutions is especially considered. Various interpolation techniques and measures of error were considered. Geostatistical methods, including two-dimensional variogramming applied to geochemical and geophysical data sets yielded interesting results which were used to outline zones of influence and to predict the occurrence or otherwise of anomalies.

Image processing methods, such as filtering, contrast enhancement, shaded relief and principal components analysis were applied to TM, geophysical, geochemical, and topographic data sets in the context of a simple image based GIS system. Several unreported geological features related to uranium mineralization were found. The study data set has been integrated on local scale and in relation to regional magnetic and gravity images.

Images derived from geostatistics and image processing were incorporated into a modified GIS structure and multivariate classification procedures, including characteristic analysis applied. This was achieved whilst retaining the utility of visual display. Models for the structural and mineralogical control on economic uranium concentration were deduced based on disciplined GIS-style queries and conclusions.

INTEGRATION OF GEOLOGICAL, GEOPHYSICAL, AND THEMATIC MAPPER REMOTE SENSING
DATA IN RELATION TO THE GEOLOGIC OCCURRENCE OF PRECIOUS AND BASE METAL
DEPOSITS IN THE ELY-HAMILTON-EUREKA, NEVADA AREA

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SUMMARY

Previous investigators have noted the E-W alignment of intermediate to felsic intrusive rocks in the Robinson Mining District. At least four separate porphyry copper ore bodies are closely associated with these intrusives. Visible faulting in the area is both parallel to and at an angle to the intrusives. Surface faults of east-west orientation are known to occur on either side of the mining district with numerous northwest-trending faults complicating the structural pattern. Over the past 3-4 years, several gold deposits have been found in and around the district. Several authors have projected this alignment of intrusive bodies to the west some 50 miles through the White Pine Mining District and called it the "Hamilton-Ely Belt." Thus, the western terminus of this "belt" would be marked by the occurrence of the long known silver-zinc deposits near Hamilton and the more recently discovered gold-molybdenum-tungsten mineralization about the Seligman and Monte Cristo stocks at the western edge of the White Pine Mining District.

The question arises as to whether or not these two districts (Robinson and White Pine) and perhaps other districts in the area are structurally and possibly magmatically related to each other. An additional and even more exciting question is whether or not the deposits west of Hamilton near Seligman are also structurally related to (an extension of or a structural flex-point/intersection with) other well known mineral belts such as the Battle Mountain-Eureka Trend and/or the Carlin Trend. To resolve these questions and others, Landsat Thematic Mapper data in combination with aeromagnetic and gravity data were digitally enhanced and examined in conjunction with existing geologic maps and preliminary geochemical data.

The geologic map data shows an alignment of intrusive bodies to the west-southwest of the Robinson Mining District including the White Pine Mining District and beyond. The gravity data showed little or no information of any consequence that was useful to this investigation. The aeromagnetic and Landsat TM data were extremely useful in delineating structural zones, the relationships of the mineral deposits along the Ely-Mount Hamilton Belt and its possible relationships to the Eureka-Battle Mountain Trend and Carlin Trend. This data, along with preliminary geochemical sampling, is also strongly suggestive of a much larger intrusive and possible porphyry copper system underlying Mount Hamilton.

BAND PREDICTION TECHNIQUES FOR THE MAPPING OF HYDROTHERMAL ALTERATION

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The availability of Landsat Thematic Mapper imagery since 1982 has improved the efficacy of satellite remote sensing in geological applications. In particular, inclusion of a spectral band centered at 2.2 μm has enabled the detection of rock and soil 'clay' signatures where vegetation cover is absent or at least not excessive. This has resulted in improved lithological discrimination for general mapping purposes but has also had direct economic implications in the detection and mapping of hydrothermal alteration haloes associated with exposed or near-surface porphyry or epithermal ore deposits.

The standard image analysis approach for the mapping of hydrothermal haloes with comparatively broad-band devices such as the Thematic Mapper or Daedalus AADS-1268 has been the band ratio technique, e.g. the 1.6 μm /2.2 μm ratio. However, band ratios operate on two image bands only and are known to suffer from formulational constraints that restrict them to qualitative image analysis. What is required is an improvement on the band ratio approach and progress towards a more quantitative estimation of the spectral anomalies of interest.

We consider three ways of predicting spectral anomalies using all six reflective bands of the Thematic Mapper: multiple linear regression, polynomial regression, and a data-adaptive linear filter. Multiple regression estimates the expected value of an image band versus the actual value as a linear combination of all the other bands, using a single set of partial regression coefficients. Thus, the drawback is that the transformation is estimated globally for the whole scene using a single set of training statistics, which is likely to be suboptimal for a specific part of the image. Polynomial regression fits a polynomial of specified degree to each pixel spectrum, to also allow us to examine some error between predicted and observed data values. We would expect this error to increase as the degree of the interpolating polynomial decreases. The transformation through the polynomial technique becomes unique for each pixel, though with some computational expense. Between these two approaches is the analyst-tuneable data-adaptive linear filter. Here, image spatial information plays a role in the calculation of the adaptive filter weights, as we expect that anomalous areas will be spatially homogeneous and have a minimum size. We would like the predictions made from neighbouring pixels to influence our prediction for the current

pixel, to assist in avoiding spurious anomalies and to provide some control over the size of predicted anomalies.

These techniques have been compared and assessed using a sample of Thematic Mapper imagery over a Precambrian porphyry system in southern Namibia -- the Haib copper-molybdenum prospect, examined by industry in the early/mid-1970's. Alteration patterns have previously been mapped and exhibit close similarity to the classic porphyry model, where the central potassic core is surrounded by phyllic and prophylic alteration haloes.

USE OF LANDSAT IMAGES FOR GEOMORPHOLOGIC, STRUCTURAL, AND TECTONIC ANALYSIS
APPLIED TO THE PROSPECTION OF MINERAL DEPOSITS
IN AN AREA OF THE IX REGION IN CHILE

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SUMMARY

The present paper belongs to a major research work developed by the Department of Physical Sciences of the Frontera University in Temuco.

The area studied is located within the borders of the Imperial River down South; the Pacific Ocean at the West; the VIII Region up North; and Cholchol River and Lumaco River at the East.

The present topic considers two priority lines of investigation: prospection geomorphology as such and Landsat images interpretation methods and topographic charts. The theoretical support of the mentioned investigation is based upon the selection of parameters to build up morphostructural, tectonic, and morphometric charts and others, in order to delimit areas plenty of possibilities to discover a kind of deposit.

Practical theory tells us that minerals are directly related to geological history and spacial structures. Nevertheless, these elements are also important in the evolution of the surface.

So, if we analyze surface in its external features such as absolute height, relatives, its dissection, its relationship between width base with height and other features which will give the information to allow us to evaluate the intensity of tectonic movements, the activity of the exogenous movements and the endurance of the surface rock of the earth, which lead us to know the geological history of the area studied as well as future views.

The existing relationship between the elements of surface and deposits, its morphostructural and morphotectonic position (location) were analyzed. The different rhythm of tectonic upheaval and different denudational speed point out to a differentiated model(ing) in the surface. Deposits come out to the surface swiftly in places of upheaval with perforated structure and they are weeded out by denudation before than other morphostructures. In those areas where tectonic movements are of less intensity, they stayed longer and their possibilities to be discovered are greater, but in areas of sinking deposit, minerals are far from the surface and become difficult to locate.

When analyzing the position of deposits in height in relation to the morphostructures, the following results were obtained: most of the deposits were located in an interval of height which

fluctuates between 500 and 800 meters and in blocks with firm tectonic tendencies -- lift up (in mesostructures) and lift retarded in its movements (in microstructures).

Most deposits are found in contact areas and from the geomorphologic point of view they are located in draining of first grade and in slopes with inclination floating between 15° and 20°.

REVIEW OF THE RELATIONSHIP OF FRACTURES TO STRESS SYSTEMS AND
THEIR IMPLICATIONS FOR REMOTE SENSING AND GEOLOGIC SPATIAL ANALYSIS

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SUMMARY

Numerous studies have shown that fracture systems control the placement of many ore bodies. Other analyses have identified fracture sets that localize oil and gas deposits. A strong tendency is to use these fracture orientations to infer the nature and geometries of ancient stress fields. However, complex relationships exist between stress systems and the geometries of the fractures that are produced by them. Different fracture orientations are created depending on whether the strain field is biaxial or triaxial. Fractures will tend to form parallel to pre-existing anisotropies, such as bedding, joint, or cleavage planes, rather than at a low angle to the earlier structures. Large structures, such as wrench faults, thrusts, normal faults, folds, salt domes, and igneous intrusives will locally reorient stress systems, modifying regional fracture patterns.

Analyses of fractures are done at scales ranging from local field studies to regional studies of joints and lineaments. A number of detailed studies have measured fracture systems in the field. These studies have shown that several hundred fractures must be measured in order to statistically define major orientations. Problems arise due to the presence of fractures created by near-surface effects which are not effective at depth. Biases in the observed orientations will also occur due to the attitudes of outcrops examined.

Lineament analyses of air photos and imagery have been extensively used in order to regionalize the observation of fractures. Lineament studies yield only the surface traces of the fractures, and not their full 3-D orientations. In order to be able to fully compare and contrast the different scales of fractures, WSU and Geologic Analysis and Consulting Services, in conjunction with Battelle PNL, is developing a state-of-the-art remote sensing software package, Geologic Spatial Analysis (GSA). GSA looks for evidence for fractures in digital data bases that can be referenced to location as well as elevation or depth. Initial versions of the GSA concept have been applied to digital elevation models (DEMs) which are scanned for valley bottoms. Valleys that trace out a vector in 3-D space may be fracture controlled. Fault and lineament traces can be registered to the DEM in order to yield vectors. Pairs of the valley or

lineament/fault vectors that lie within the same plane define potential fracture orientations in 3-D space. Because GSA defines 3-D fractures by examining correlations of vectors across an entire topographic quadrangle, it can be used to infer the nature of regional stress systems.

GSA has been applied to several study areas where detailed field studies of fractures exist. In northeastern Washington, field mapped fractures have been correlated to GSA studies on 1:24,000 and 1:250,000 scale DEMs. At the Cajon Pass, California deep continental drillhole site, fractures in the borehole and on the surface are being compared to 1:24,000 scale DEMs. While the major orientations of the structures, and the stress fields inferred from them, are similar on the different scales, there are some important differences between them.

SOME CORRELATIONS BETWEEN LABORATORY SPECTRA AND MULTISPECTRAL
THERMAL IMAGERY OF EVAPORITE MINERAL DEPOSITS IN DEATH VALLEY

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SUMMARY

The floor of Death Valley is a vast evaporating dish crusted over with a variety of salts arranged in concentric zones reflecting their different solubilities. Near the outer margin of the valley floor lie carbonate and sulfate zones. In the central part of the salt pan is a chloride zone comprising about three-quarters of the valley floor. This latter zone consists principally of NaCl. However, minor concentrations of soluble species such as magnesium sulfate, together with other wind and water borne contaminants also occur in this area.

Pure NaCl is totally devoid of spectral features in the 8-14 micrometer wavelength region; however, previously published color composite multispectral thermal imagery of the salt pan depicts the chloride zone in several colors, suggesting absorption by species other than NaCl.

Spectral properties of particulate minerals dispersed in a nonabsorbing material such as NaCl can be very different from those of the isolated minerals. A practical result of this for thermal infrared remote sensing of highly saline areas is that interpretations should be based on spectral properties of appropriate samples approximating the natural composition of the terrain rather than on pure mineral samples.

To illustrate this, laboratory reflectance data for particulate samples of calcite, gypsum, quartz, and montmorillonite in various mixtures with NaCl were averaged over the spectral regions corresponding to those of channels 1, 3, and 5 of the JPL TIMS sensor. These data were converted to approximate emittance values using Kirchoff's relation, $E = 1 - R$. Predictions of colors which might be expected in a hypothetical three color composite image using these data with channels 1, 3, and 5 displayed blue, green, and red, respectively, are compared with published TIMS imagery. A number of correlations are noted.

THERMAL-INFRARED SPECTRA AND IMAGERY OF ALTERED VOLCANIC ROCKS
IN THE VIRGINIA RANGE, NEVADA

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SUMMARY

Thermal-infrared multispectral scanner (TIMS) data and laboratory thermal-infrared reflectance spectra were collected from sites of hydrothermally altered andesitic volcanic rocks associated with silver and gold mineralization near Virginia City, Nevada. Alunitic, kaolinitic, illitic, and propylitic alteration types have distinguishing laboratory spectra, although the individual spectral are difficult to interpret mineralogically because many of the silicate minerals have overlapping spectral features in the 8-12 μm wavelength region. The general shape of the spectral curves appears to be due to combinations of features caused by the key minerals quartz, kaolinite, pyrophyllite, illite and/or montmorillonite and/or sericite, feldspar, and chlorite. X-ray diffraction and petrographic techniques were used to identify mineral phases in each type of alteration.

TIMS radiance and temperature spectra were highly correlated between channels, due to surface temperature variations. TIMS emittance values using atmospheric correction factors calculated from a general mid-latitude summer LOWTRAN model were not accurate, especially at shorter wavelengths. TIMS normalized emittance spectra were constructed assuming a constant emittance at 11.5 μm and that a vegetated site in the TIMS scene was spectrally flat in the 8-12 μm wavelength region. The normalized emittance spectra show a general shift in the wavelength position of the silicate emittance minimum to shorter wavelengths with increasing alteration, due to the increasing abundance of secondary framework and sheet silicate minerals such as quartz and clay minerals. Strongly altered volcanic rocks are identifiable on TIMS radiance and emittance imagery processed using a decorrelation-stretch technique with channels 3, 4, and 5.

This study provides additional evidence that thermal-infrared laboratory and aircraft multispectral scanner data are effective in identifying and mapping hydrothermal alteration that may be associated with mineralization in volcanic terrains.