THEMATIC CONFERENCES ON REMOTE SENSING
FOR EXPLORATION GEOLOGY

ATTACHMENT
A

SUMMARIES

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ATTACHMENT B

[Session 5 & C-2]

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.

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.

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.

ATTACHMENT C

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 paleo-topographic 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.

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 proprietory 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.

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 testec 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 focusec 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.

REMOTE SENSING DETECTION OF HYDROCARBONS AND HYDROCARBON SEEPS

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SUMMARY

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 ~1.7 μm, 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.

Acknowledgements: This study and the researcher were supported by a grant and scholarship from the Alberta Oil Sands Technology and Research Authority (AOSTRA), and a Grant-in-Aid (#582-12-01) from the American Association of Petroleum Geologists.

ATTACHMENT D

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.

M

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 discuses 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 ration of TM3/TM1. Our final product is a paper map suitable for copying or dyeline 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.

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.

ATTACHMENT E

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 intepretation 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.

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 N60W 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.

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 instrusives. 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.

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.