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EVALUATION OF LANDSAT-2 (ERTS) IMAGES APPLIED TO GEOLOGIC STRUCTURES
AND MINERAL RESOURCES OF SOUTH AMERICA

William D. Carter
U. S. Geological Survey
Reston, Virginia

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Type II Progress Report for Period March 14, 1975 - June 30, 1975

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TYPE II PROGRESS REPORT

LANDSAT-2

A. PROBLEMS:

1. The first shipments of LANDSAT-2 data that were received by this project had a significant number of line drops. This was also true of several CCT's that were ordered for project areas in Bolivia and northern Chile. A study of the images showed that the highest number of faulty images were coming from the Fairbanks receiving station, fewer were coming from Goldstone and the least from the Goddard receiver. A memorandum dated March 1975 (attached) to NASA via T. Ragland explaining the problem and suggesting that a receiver problem may exist rather than a satellite tape recorder problem. No response to these observations has yet been received from GSFC.

Four tapes having the line drops were sent to F. Billingsley and A. Goetz at JPL, Pasadena, where they were reformatted and processed by the ERTS/FIX program which made them operable. These were tested on the Image 100 at the EROS Data Center and found to be excellent.

B. ACCOMPLISHMENTS:

1. Five CCT's have been processed employing the Image 100 system. The first tape (E-1447-14073) covering Lake Titicaca in parts of Peru and Bolivia was processed for multidiscipline demonstration purposes

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on the GE system at Beltsville at a cost of \$2250 (\$250/hr.). The test results provided information on wetland vegetation distribution, ground water effluents, river effluent sedimentation distribution, mine dumps and workings, as well as bedrock outcrop patterns. These encouraging results have been described in a paper by Carter and Brockmann (see reports) that was presented at the XVII COSPAR Meeting, Varna, Bulgaria, (June, 1975), and is to be published in Remote Sensing of the Environment or some other outlet.

2. Processing of other tapes (Lago Poopo, Salar de Uyuni, Salar de Ascotan, Salar de Atacama, Chuquicamata, and Mejillones) have been aimed at subdividing the major salt lakes which, on standard processed images, are generally shown as a uniform white. As many as nine units or themes were developed for the Salar of Uyuni. The alteration zone of the San Juan del Abra porphyry copper deposit was successfully separated on the basis of radiance values. These thematic maps are being distributed to corresponding scientists in Bolivia and Chile for evaluation and field checking.

3. LANDSAT-2 data is being received for important regions of Peru and Chile. Excellent data for the Santiago-Mendoza region are now in hand for the entire 4 x 6 degree quadrangle area. Estimates for preparation of a mosaic are being prepared by the Special Mapping Center of the Topographic Division of the Survey. Hopefully, this experimental map will be printed in color.

4. During the report period, the following activities were accomplished:

a. On January 27, 1975, I presented a 1 1/2 hour lecture on the Applications of LANDSAT Data to Geologic Mapping and Environmental Monitoring at U. S. Army Topographic Command remote sensing training course at Harper's Ferry, West Virginia.

b. Between February 4-6, 1975, I presented a 3-day short course for CETENAL, a government mapping agency in Mexico City. The lecture, sponsored by the American Association of Petroleum Geologists' Continuing Education Program, was conducted in Spanish and consisted of a 3-hour lecture in the morning and a 3-hour hands-on-data workshop in the afternoon of each day. Thirty participants of the agency took the course.

c. On March 11, 1975, I presented a paper at the Annual Meeting of the American Society of Photogrammetry entitled, "LANDSAT(ERTS)-1 Applications to the Discovery of Energy Resources, Development and Utilization." Copy of paper attached to this report (Attachment A).

d. During the period of April 7-11, 1975, I traveled to San Jose, Costa Rica, to confer with USAID and Costa Rican officials on cadastral survey problems in the Chacambú area, northcentral Costa Rica. I described the possibility of using LANDSAT and SLAR data as an alternative to standard aerial photography for mapping

land use development in a persistently cloud-covered area. A 2-hour talk on remote sensing was presented to Costa Rican, InterAmerican Bank, and U. S. officials.

e. Between May 7-9, 1975, I presented a 9-hour training course in remote sensing to the Wyoming Geological Association, Casper, Wyoming, under the AAPG Continuing Education Program. Dr. Ron Marrs, Wyoming Geological Survey, also presented a 2-hour lecture at the end of the period. Approximately 90 geologists attended the course.

f. Between May 18-20, 1975, I attended the University of Wisconsin, Madison, Wisconsin, Workshop on Critical Areas. At the workshop, I gave a talk on "The Applications and Flexibility of Use of LANDSAT Data for Monitoring Critical Areas." I stressed the use of CCT's in large-scale mapping.

g. Between May 27 and June 7, 1975, I attended the 18th Plenary Meeting of COSPAR, Varna Bulgaria, and presented a paper entitled, "Preliminary Evaluation of an Interactive Multispectral Image Analysis System - Lake Titicaca Region, Bolivia and Peru" by W. D. Carter and C. E. Brockmann. A copy of this paper is Attachment B.

h. On Monday, June 16, 1975, I presented a paper entitled, "Small-Scale Image Mosaics: An Aid to Plate Tectonics Studies" in the Tectonophysics-NASCA Plate session of the American Geophysical Union 1975 Spring Annual Meeting. A copy of the abstract is Attachment C.

5. Work has continued, albeit slowly, on the final report of this project on ERTS-1 data. A draft copy submitted to NASA/GSFC was accepted, but final approval by USGS is still not acquired. It should be completed soon.

6. At my suggestion, the EROS Program sponsored a 1-week workshop on Data Collection Platform Systems at IAGS Headquarters, Fort Clayton, Panama. A team of U. S. experts, including R. Paulson, D. Preble of USGS, E. Painter, NASA/GSFC, and Glenn Conover of Dorsett Electronics conducted the experimental workshop. Thirty participants from Latin American countries attended and were most enthusiastic about the possibilities of introducing such monitoring techniques in their respective countries. Test projects have been started in Bolivia and Chile. The tracking station at Santiago is being modified to receive such data and similar renovations are being considered at Ancon, Peru and Quito, Ecuador.

A cooperative DCP experiment has been developed with Bolivia and Chile. The Colinas Tracking Station at Santiago has been modified to receive DCS data. C. Brockmann of GEOBOL, La Paz, Bolivia, has been loaned DCP #6312 and it is installed and operating at the University of San Andres astronomical observatory at Patacamaya ($67^{\circ} 54' 43''$ W and $17^{\circ} 15' 42''$ S). It will measure water levels, stream flow, and at this time, no signals have been successfully transmitted or received. This may be due to the fact that the data

relay system on the satellite is customarily shut off as it passes over the Caribbean Sea. The first signal from Bolivia was received by the Colinas Tracking Station on September 30, 1975.

C. SIGNIFICANT RESULTS:

1. Work with the Image 100 clearly demonstrates that radiance values of LANDSAT data can be used for correlation of geologic formations across international boundaries. The Totora Formation of the Corocoro Group of Tertiary age was traced from known outcrops near Tiahuanaco, Bolivia, along the south side of Lake Titicaca westward into Peru where the same rocks are considered to be Cretaceous in age. This inconsistency suggests:

a. that a review of this Formation is needed by joint geological surveys of both countries to determine similarities, differences, and the true age;

b. that recognition of the extension of the copper-bearing Totora Formation of Bolivia into Peru may provide Peru with a new target for exploration.

2. Equal radiance maps made by use of the Image 100 system show as many as eight different units within salar deposits (salt flats) of the Bolivian Altiplano. Standard film processed images show them as nearly uniform areas of white because of lack of dynamic range in film products. The Image 100 system, therefore, appears to be of great assistance in subdividing the salt flats on the basis of moisture distribution, surface roughness, and distribution of windblown materials.

Field work is needed to determine these relationships to mineral composition and distribution. Images representing seasonal changes should also improve the accuracy of such maps. The radiance values or themes developed for these deposits were also tested by W. Kowalik on CCT's of the Buena Vista Valley of northwestern Nevada and found to be correlatable in part. This suggests that standard units may be developed and used on a hemispherical or worldwide basis.

3. Radiance values of alteration zones related to the occurrence of porphyry copper ores were measured at the San Juan del Abra deposit of northern Chile using the Image 100 system. We have not yet tested the extent to which these same values may be used to detect similar alteration zones in other areas.

D. PUBLICATIONS:

Carter, W. D., 1975, Small Scale LANDSAT Image Mosaics: An Aid to Plate Tectonic Studies: (Abstract), EOS-Trans. Amer. Geophys. Union, vol. 56, no. 6, p. 442, Art. T-14.

Carter, W. D., 1975, LANDSAT(ERTS)-1 Applications to the Discovery of Energy Sources, Development and Utilization: (Abstract). American Soc. Photogrammetry Annual Meeting, Washington, D. C., March 1975.

Carter, W. D. and Brockmann, C. E., 1975, Preliminary Evaluation of an Interactive Multispectral Image Analysis System - A Study of the Lake Titicaca Region, Bolivia and Peru: (Abstract), Program Abstracts, 18th Plenary Meeting COSPAR, Varna, Bulgaria, May-June 1975, p. 420-421.

Williams, Jr., R. S. and Carter, W. D. Editors (in press), ERTS-1: A New Window on Our Planet: U. S. Geological Survey Prof. Paper 929, 400 p. 250 illus.

E. RECOMMENDATIONS

The requirements for complete cloud-free LANDSAT coverage of South and Central America and the Caribbean Islands are steadily growing. The needs for repetitive coverage in several areas are being defined. There is also a growing interest in the use of remote surface data through the use of DCP's in the Andes and Amazon Basin.

It is recommended that serious consideration be given by NASA, the U. S. Geological Survey and other cooperating agencies to the following:

1. Feasibility studies for construction of a receiving station in northern Venezuela, Colombia, or some other suitable site in the Caribbean to provide complete realtime coverage of the area between the Brazil reception station and U. S. stations. A similar study should consider the area of southern Chile, Argentina, and the Palmer Peninsula of Antarctica.

2. That existing tracking stations at Quito, Ecuador, Ancon, Peru, and Colinas, Chile, be upgraded to accept DCS data on a realtime basis. The Cuiaba Station in Brazil should also be encouraged to upgrade its station to accept such data.

F. FUNDS EXPENDED:

TRAVEL - **Costa Rica - April 7 - 11, 1975**
 \$575.64 - Paid by AID
 Madison, Wisconsin - May 18 - 20, 1975
 \$220.09
 Bulgaria - May 27 - June 7, 1975
 \$1,440.73

Total travel for period March 14, 1975 - June 30, 1975
 \$2,236.46

DATA ANALYSIS - \$2400

DATA PROCESSED - \$4631

TOTAL - \$9267.46

G. DATA USE:

The following tabulation shows the value of the data estimated for the project and the data received during the report period.

<u>Value of Data Allowed *</u>	<u>Value of Data Received</u>	<u>Balance Remaining</u>
\$16,400	\$4,631	\$11,769.00

*Account No. G-23010

LANDSAT (ERTS)-1 Applications to the Discovery of
Energy Sources, Development and Utilization

William D. Carter
EROS Program
U. S. Geological Survey
Reston, Virginia 22090

The Earth Resources Technology Satellite (ERTS-1), now called LANDSAT, provides synoptic, repetitive and multispectral views of large areas of the Earth's surface. These views are especially useful in unmapped or poorly mapped regions of the world which are now being tapped for energy resources (coal, petroleum, water). Its application to the discovery of geothermal sources is being explored. It has been found that ERTS is also a useful tool in monitoring the extent of development of coal stripping operations and recovery of the land by reclamation practices.

The uses of energy for power and industrial production create products, both primary and secondary, which generally express themselves as land fill deposits, thermal and sediment plumes in water bodies. While LANDSAT does not yet have a thermal capability, repetitive images have shown changes and phenomena related to energy use and should be considered as an information source in any monitoring system.

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INTRODUCTION

This paper is intended to serve as a summary report on the status of the minerals and energy resource industry and related governmental agencies in their use of remote sensing data, and especially LANDSAT (ERTS) data, as a tool in exploration, management and reclamation. It is not intended to be all-inclusive but merely an overview of highlights. Hopefully it will stimulate ideas for further research.

In mid-February 1975 a conference on remote sensing case histories, co-sponsored by the American Association of Petroleum Geologists, U. S. Geological Survey, and University of Kansas Program for Continuing Education, was held in the new Nichols Building of Space Technology, University of Kansas, Lawrence, Kansas. It was attended by 120 geologists and geophysicists representing mining and petroleum companies, universities, State and Federal government agencies. It is significant to note that there was much interest in the conference and that over 150 applicants had to be turned away because of limitations of the auditorium selected. Of 27 papers presented, 12 described specific techniques or case histories of actual exploration projects either completed or underway. The remainder were state-of-the-art summaries of techniques or research efforts to develop the state-of-the-art, and supporting activities. Two papers were on the use of side-scan sonar in petroleum exploration of marine areas. While this conference did by no means include all known applications of remote sensing to mineral and petroleum exploration,

it did much to provide a focus on the current situation and several are cited in this report. Other sources, known to the author, are also included where appropriate.

LANDSAT (ERTS-1) DATA

Synoptic Views

LANDSAT imagery is inexpensive, easily available, and nearly worldwide in coverage and provides broad synoptic multispectral views of large areas. For these reasons it is now being widely used by petroleum and mineral exploration groups whether they be industrial corporations, consultants or national organizations. It is especially useful in remote regions of the world where base maps may be poor to nonexistent. It has also been found useful in well-known regions such as oil-producing areas of the United States where a broad regional view is providing a reinterpretation of major structural features or identification of surface phenomena that have previously gone unnoticed.

For example, John Miller⁽¹⁹⁷⁵⁾ of Chevron Overseas Petroleum, Inc., cited an example of how LANDSAT data was used to provide a geologic interpretation of structural features and lithology on the Chevron-Kenya oil license covering parts of the Lamu Embayment of Kenya. The area lies northeast of Lake Victoria at the intersection of the northeast trending Bier-Acaba Ridge and the northwest trending Rudolph Trough. Not only did satellite data provide an overview of the regional geological setting but it improved the definition of

anomalies and lineaments that were significant to interpretation of structure and stratigraphy of the area and established guides to exploration.

Similar results were found by U. S. mining companies operating on leases in Tunisia, Egypt, Yemen and Sumatra. Oil companies operating in the headwaters of the Amazon Basin on leases offered by the Bolivian and Peruvian Governments have found that LANDSAT (ERTS) data is often the only base map available for the region. In all cases cited above the data was useful in selecting exploration targets and reducing the amount of "blind" exploration which is often dangerous, tedious, and expensive.

Dr. Eduardo Gonzales (personal communication) of the Empresa Nacional de Petroleo of Chile (Chilean National Petroleum Co.) was able to mosaic small, cloud-free portions of several LANDSAT images of the Magallanes area. With this he was able to define a new basin which he suspects is filled with Tertiary sedimentary rocks. Elsewhere such rocks are host-rocks for petroleum in south Chile.

In spite of the fact that each LANDSAT image provides synoptic views of areas covering 34,225 square kilometers, investigators find that mosaics covering larger areas often provide significant and new information. For example, Ing. Guillermo Salas⁽¹⁹⁷⁴⁾ of the Mexican Consejo de Recursos Naturales No-Renovables, using a mosaic of Mexico, demonstrated that most major mineral producing areas were located at intersections of prominent northwest trending lineaments with northeast trending lineaments.

Mosaics and images of the Andean region, made as part of a NASA-sponsored experiment by the writer, have been purchased by exploration companies to aid their work. Lineament interpretations of the La Paz Mosaic (16-20° S and 66-72° W) made from Band 6 images, have been selectively field checked by Bolivian Government geologists who found fractured outcrops of Totora Sandstone (Tertiary) mineralized with chalcocite and malachite. A detailed exploration and sampling program was then designed along the 20 km length of a linear for further field confirmation. The results of these studies are not yet known.

A mosaic of the United States made by the U. S. Department of Agriculture has been studied by a number of geologists including this writer. Dr. Robert A. Hodgson (1975) of Gulf Research and Development Company, Pittsburgh, Pa., reported at the Kansas University conference on his interpretation of lineaments seen on the mosaic as published in Geotimes. While there were some significant differences between his interpretation and that of this writer, there were many more similarities. Both interpreters independently reached the conclusion that they were "seeing" surface expressions of fundamental geologic structures, many of which appear to have been repeatedly expressed through geologic time. Some features, if verified, may require modification of current theories of crustal deformation.

In an effort to evaluate such interpretations, the U. S. Geological Survey has undertaken a complete study of the conterminous United States from a mosaic produced at a scale of 1:1,000,000 using

Band 7 (infrared) images. Three separate interpreters, all experienced geologists, studied each of 17 sheets and their results are being compiled into a single overlay with line weights corresponding to 1, 2 or 3 interpreter coincidence. Seven selected 2-degree quadrangles within this compilation are being enlarged to a scale of 1:250,000 and will be sent to USGS field geologists responsible for field mapping the published 2-degree sheets. Their evaluations and comments will be used to determine whether the project should continue to completion. Hopefully, their evaluations will be available within the next three months.

Alternative Methods

Where clouds present difficulties in obtaining suitable LANDSAT (ERTS) data, exploration firms have used Ka- and X-brand imaging radar systems to advantage. Norman H. Foster of Filon Exploration Corporation, Denver, Colorado, and R. A. Soeparjadi, Pertamina, Jakarta, Indonesia, report that aerial color infrared photography and side-scan radar were used to identify oil-bearing pinnacle reefs in the Salawati Basin of Irian Jaya, Indonesia. Success of the survey was based on the fact that the pinnacle reefs are surrounded by and overlain by several hundred feet of clay shale which, by differential compaction and erosion, permit the reefs to be expressed geomorphically as low hills 100-200 feet high that deflect or modify the courses of meandering streams. Such features are readily observed by the low-illumination angle of radar.

(1975)

R. S. Wing and J. C. Mueller, Advance Exploration Group, Continental Oil Company, reported on the use of radar images in

another part of Irian Jaya, Indonesia. CONOCO's contract area, covering 53,625 km², was flown in April 1973 using the Westinghouse K-band system in north-looking strips with 60% overlap to provide stereo coverage. Sinuous gentle folds in the foothills of the Irian Range in the eastern portion of the contract area appear most promising for the accumulation of hydrocarbons.

William M. Ryan and Gordon Owens of the Columbia Gas Corporation reported on the use of SLAR in western Virginia and southeastern Kentucky where Columbia's Haysi Field was studied to determine the relation of open flows and gas production to natural fracture zones. The area lies at the eastern edge of the Pine Mountain overthrust and the main producing formation is the Berea siltstone at an average depth of 4,000 feet. Average porosities range from 3 to 7% but open flows of over 3,000,000 cu.ft./day have been found. Studies of lineament patterns, using both radar and aerial black and white infrared film, showed a close correlation between highly productive wells within 1500 feet of major linear features and less productive locations more than 1500 feet from them.

Multispectral bands

Attempts to fully utilize the multispectral aspects of ERTS are still very much in the beginning stages. Dr. Gioberto Amaral (1974) of Brazil found that standard color composite prints or Band 7 images display "canga," iron-rich surface alteration of itabirite iron deposits in vegetated areas of Brazil as dark patches indicating absorption of light rays. Bakkila and Reynolds of U. S. Steel

(personal communication) noted that distinct vegetation differences can be recognized on ERTS images between heavily vegetated andesite porphyry and poorly vegetated nickeliferous laterites on Gag Island, where the company is operating a mineral development lease in Indonesia. Quantitative signature analysis is being developed over such areas using interactive computers such as the General Electric Image 100 to determine if this method can be used as an exploration tool.

Rowan and others (1975) have experimented with processing of LANDSAT computer compatible tapes using computer programs developed by the Jet Propulsion Laboratory at California Institute of Technology. By developing ratios between bands and compositing them together as false-color products, they found it possible to enhance alteration zones associated with the Goldfield, Nevada, ore deposits. They were also able to identify similar areas of alteration within the region that have since been verified in the field.

R. G. Schmidt,⁽¹⁹⁷⁵⁾ of the U. S. Geological Survey, used computer techniques developed in IBM research laboratories by Dr. Ralph Bernstein, to develop criteria for identifying potential porphyry copper deposits in Pakistan. Of fifteen areas selected by this analysis, ground studies indicated that five were considered sufficiently promising for detailed studies and additional exploration.

The writer, using the Image 100 system, was able to develop a "signature" for the Totora Sandstone of Bolivia and extend it throughout the Lake Titicaca scene. The outcrop pattern corresponds well with the unit as mapped in Bolivia but needs to be confirmed by field observation in the Peruvian portion of the scene.

(1975)

Terrence Donovan has described the U. S. Geological Survey's Project Birddog (Basic Investigation of Remotely Detectable Deposits of Oil and Gas), an experimental program to develop an integrated remote sensing-geochemical petroleum exploration technique. Previous and on-going research demonstrates that imperfect rocks capping petroleum and natural gas deposits may permit large volumes of low molecular weight hydrocarbons to escape to the surface, causing surface alterations that may be expressed as oxidation products, cementation, isotopically distinctive precipitates or discolorations of surface strata by reduction or dissolutions of iron. These late diagenetic alteration phenomena reflect subsurface distribution of petroleum. The "Cement" Oil Field of Oklahoma, for example, is capped by Peruvian sandstone which is normally red, but over the field progressively grades to tan, white and light gray near the crest of the structure. The Davenport Field (T14 and 15N, R5E) Oklahoma is a combination structural and stratigraphic trap where unusual carbon and oxygen isotopic compositions are found in dolomitic sandstone of Peruvian age. Iron oxides of the surface rock progressively diminish toward the crest of the structure. A number of computer processing techniques are being applied to LANDSAT-1 images to enhance and develop identifying "signatures" for that phenomena. RB-57 and U-2 data have also been supported by low altitude underflights, field mapping geophysical measurements, and laboratory analysis.

Repetitive Data

While LANDSAT-1 can theoretically provide coverage of most areas on the Earth every eighteen days and in the higher latitudes as frequently as 5 days, this capability has not yet been used to any great extent by geologists in mineral or petroleum resource exploration.

Some geologists are testing seasonal images and have found that winter images with light snow cover can be useful to define lineaments, especially in areas of the mid-continent region where topographic relief is moderate to small. Morrison (1974) found it useful in mapping glacial and outwash terrain in the midwest. Krinsley (1974) found repetitive seasonal data extremely useful in studies of the Qom Playa and other ephemeral salt lakes of Iran. He was able to demonstrate their use in planning a new highway route across a large unpopulated desert region.

Carlson (1975) and Hunter (1974) studied sediment distribution patterns of river effluents to the Pacific and Gulf Coast, respectively, and the effects of winds and currents on deposition. These studies could be useful in locating near-shore marine placer deposits and could also serve as a guide to oil companies drilling in nearshore areas to determine the most likely fate of spills or other accidents.

Numerous investigators have found that in semi-arid areas geologic features are more visible after rainy periods when soil moisture is high. A notable example is provided in scenes of the Witwatersrand area, west of Johannesburg, South Africa.

As exploration for marine petroleum deposits extends into Arctic regions, our knowledge of the location and movement of ice and ice leads will become increasingly important. Canada has installed a quick-look capability at their Prince Albert reception station to provide Arctic shipping information within 48 hours. Barnes and Bowley (1975), Anderson (1974), and Campbell (1974), have clearly demonstrated the value of ERTS image to monitor drift of ice floes and development and changes in ice leads in very short periods (hours) of time. by use of closely spaced repetitive data.

Environmental Monitoring

The multispectral and repetitive capability of the LANDSAT system is also proving to be an effective tool in environmental monitoring. Lathram (personal communication) has studied color composites of the area near Umiat, Naval Petroleum Reserve No. 4, in northern Alaska, where extensive bulldozing for trails and other activities took place during the late 40's and early 50's. He concluded from the images that most of the old scars had essentially healed during the past twenty years. His conclusions were confirmed by field inspection during the summer of 1974. It, therefore, appears that LANDSAT data can be used to monitor the effects of construction and other activities related to the Aleyaska Pipeline and petroleum development in the Arctic.

Rehder (1973 a & b) has demonstrated the use of temporal data in monitoring strip mine activity in the Appalachian region. Not only was it possible to map the development of new mining areas, but it

is also possible to observe progress in reclamation of the land to other uses. Near Pittsburgh, for example, several old strip mines have been converted to golf courses - and appear as pink areas, indicating vigorous vegetation.

This capability has been adopted by the U. S. Bureau of Mines as part of its program to monitor all the coal strip mines of the United States and the U. S. Army Corps of Engineers is using LANDSAT data in its program to map and assess all the water impoundments. The Bureau of Land Management is using such data to monitor the environmental effects of strip mining on public lands in Wyoming and Montana.

Industrial wastes from paper mills and mineral processing have also been observed in LANDSAT images. The Laboratory for Remote Sensing at Purdue University is completing a study of the Great Lakes Basin for EPA. Its goal is to map land use and determine the source of major pollutants to the lakes. A paper mill in New York State was cited in a legal suit by the State of Vermont for dumping mill sludge into Lake Champlain - as observed on LANDSAT images.

Oil slicks due to barge and tanker accidents have been observed in numerous images around the world. One of the earliest reported was by Joe Otterman of Israel in his studies of the Red Sea.

CONCLUSIONS

LANDSAT data, because it provides uniform, repetitive, multi-spectral information, is a basic system for large area regional studies. It complements aerial and ground geophysical information gathering systems. It can be used in image analog or digital form ranging from 1:3.6M to 1:25,000 scales. Most standard image products

are at scales of 1:1,000,000, 1:500,000 and 1:250,000. Computer compatible tapes increase its flexibility by providing reflectance values of individual pixels and greater scale (1:25,000) through the use of interactive computer systems. Ratio processing and other enhancement techniques are rapidly developing.

The uses of LANDSAT data in mineral and energy resource exploration have been tested during the past 2 1/2 years. LANDSAT data is quickly passing from an experimental to an operational exploration tool, especially in the more remote regions of the world. Geologists are finding that the LANDSAT data system has great flexibility displayed as images or mosaics at many scales or in digital form with interactive computer systems. Its full potentialities as an exploration and monitoring system are still being explored and hold considerable promise.

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**Preliminary Evaluation of An Interactive
Multispectral Image Analysis System
A Study of the
Lake Titicaca Region, Bolivia and Peru**

**by William D. Carter
EROS Program
U. S. Geological Survey
Reston, Virginia 22090
and
Dr. Carlos Brockmann
Programa ERTS-1 Bolivia
Servicio Geológico de Bolivia
La Paz, Bolivia**

ABSTRACT

ERTS-1 digital data in the form of computer compatible tapes provide the geoscientist with an unusual opportunity to test the maximum flexibility of the satellite system using interactive computers, such as the General Electric Image 100 System. Approximately 9 hours of computer and operator time were used to analyze the Lake Titicaca image, 1443-14073, acquired 9 October 1973. The total area of the lake and associated wetlands was calculated and found to be within 3 percent of previous measurements. The area was subdivided by reflectance characteristics employing cluster analysis of all 4 bands and later compared with density values of band 4. Reflectance variations may be attributed to surface roughness, water depth and bottom characteristics, turbidity, and floating matter. Wetland marsh vegetation, vegetation related to ground-water effluents, natural grasses, and farm crops were separated by cluster analysis. Sandstone, limestone, sand dunes, and several volcanic rock types were

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similarly separated and displayed by assigned colors and extended through the entire scene. Waste dumps of the Matilde Zinc Mine and smaller mine workings were tentatively identified by signature analysis.

Histograms of reflectance values and map printouts were automatically obtained as a record of each of the principal themes. These themes were also stored on a work tape for later display and photographic record as well as to serve in training.

The Image 100 system is rapid, extremely flexible and very useful to the investigator in identifying subtle features that may not be noticed by conventional image analysis. The entire scene, which covers 34,225 km², was analyzed at a scale of 1:600,000, and portions at 1:98,000 and 1:25,000, during a 9-hour period at a rental cost of \$250 per hour. Costs to the user can be reduced by restricting its uses to specific areas, objectives, and procedures, rather than undertaking a complete analysis of a total scene.

INTRODUCTION

LANDSAT 1 and 2 multispectral scanner data are synoptic records of the radiometric properties of objects and features on the surface of the earth. These records are received from the satellite as electronic signals and are subsequently converted to film as analog images or stored on computer compatible tapes (CCT's) for further processing and display either as video images or as line-printer thematic products having the geometric characteristics of a map.

Both types of data have been evaluated in this experiment dealing with the structural geology and mineral resources of the Andes Mountains of South America. The experiment is a cooperative effort between the U. S. Geological Survey and similar agencies of the participating countries (Peru, Bolivia, Chile, and Argentina). This paper deals with the preliminary results of analysis with an interactive multispectral image analysis system, known as the Image 100, built by the General Electric Company^{1/} It is one of several similar instruments that are now available for use, and it is the intent of this experimental project to evaluate each analysis system from the "user" and especially the geologists' viewpoint.

OBJECTIVES AND BACKGROUND OF EXPERIMENT

The objective of this experiment was to determine how the General Electric Company Image 100 Interactive Multispectral Image Analysis System could assist the geologist in extending his limited knowledge of an area within an entire ERTS scene (34,225 km²). In this case, it was decided to not only study the distribution of certain rock types, but also surface water distribution and variation and wetland and agricultural vegetation. The scene selected was image (1443-14073 (Oct. 9, 1973) which covers all of Lake Titicaca and adjacent areas of Bolivia and Peru.

1/ Designation of commercial scientific instruments in this report is for purposes of identification only and does not constitute an endorsement by the U. S. Government.

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Titicaca

Lake Titicaca, the largest inland body of water in South America, lies within a drainage basin that covers 56,300 km² (Wijs, 1944). It is the highest navigable lake in the world. The altitude of the water surface has been reported to range from 3,802 to 3,808 masl (Bazoberry, 1969). The average from 1918-1966 was 3,808 masl. With each meter of vertical change, the surface area changes approximately 250 km² (Bazoberry, 1969). Annual precipitation records (1910-1943) show a range from 541 mm to 935 mm per year. Evaporation records (1910-1943) show a range from 1032 mm to 1700 mm per year. Average inflow rates, originating largely from the northern Cordillera Real, from 1915-1929 were calculated as 1363.1 mm/yr (379 m³/s). Brockmann (pers. comm.) states that Lake Titicaca covers an area of 8100 km² from planimetric measurements made on image 1191-14093, dated Jan. 1, 1973, which corresponds to the rainy period. Bazoberry (1969) calculated a surface area of 8,171 km² by planimetry from existing maps of the area. The average annual temperature is 10° C.

The geology of the area is highly complex but can be summarized as a broad synclinal basin trending approximately N50W. Complexly folded and faulted rocks ranging in age from Silurian to Tertiary comprise the eastern Cordillera, northeast of the lake. Folded Cretaceous and Tertiary sedimentary rocks occupy the basin northwest and southeast of the lake, respectively. Cenozoic volcanic rocks comprise the surface materials of the western Cordillera. Where exposed near the Pacific Coast, the underlying rocks are largely

Jurassic and Cretaceous volcanic rocks intercalated with marine limestones. They dip monoclinally to the east or are intensely faulted into irregular blocks. Acidic intrusive rocks of Mesozoic/Cenozoic age crop out as irregular masses both east and northwest of the lake.

The valleys at the Bolivian end of Lake Titicaca are broad and although sparsely populated are extensively farmed. Potatoes and grains (cebada, avena) are the principal products. Local people use the tall marsh grass (totora) from the wetland areas at the margin of the lake to make their distinctive reed boats.

SYSTEM DESCRIPTION

The Image 100 system consists of 7 basic units. Two tape-drive units permit access to the computer compatible tapes (CCT's) which are read one by one into an associated television screen or video display unit. A disk Dec recorder permits one to record and store thematic extractions derived during the analytical procedure. A memory core unit, a hard-wired program unit, and the video display unit are all tied into a programming typewriter which has a CRT on which programs and histograms are displayed and which provide interaction with the image scene.

Ancillary equipment includes a rotatable light table with television camera mounted in a vertical^a position to superimpose film images or maps into the video display unit enabling comparison

with temporal data or published maps and other source data. A Tektronix printer provides paper printouts of program procedure or histograms displayed on the typewriter CRT for documentation of the analytical steps undertaken. A line printer also provides paper copy of themes that have been extracted.

DATA FORMAT AND ANALYSIS PROCEDURE

There are four computer compatible tapes for each LANDSAT image (Fig. 1). Each tape is 9 track, 800 bpi and contains 4 spectral bands (MSS 4 - 0.5 to 0.6 μm ; MSS 5 - 0.6 to 0.7 μm ; MSS 6 - 0.7 to 0.8 μm ; MSS 7 - 0.8 to 1.1 μm) of one quarter of the scene in strips representing a ground track 46 km wide and 185 km long from north to south. Higher density tapes having 1600 bpi can also be obtained for computers capable of processing them.

Tape 1 parallels the west edge of the scene and tapes 2, 3, and 4 progress eastward to the east edge of the scene. They may be displayed singly or stored in memory and combined by systematic pixel sampling to provide a full scene overview. Because the video screen is a standard 500 line color television tube, a full screen display uses only every 30th pixel (picture element) of the approximately 7.5 million pixels that comprise a total scene. Generally, it is desirable to store and initially display the full scene to provide an overview which the scientist and instrument operator (the investigation team) use to discuss the experimental plan and to select smaller areas or subscenes that will be studied in greater detail.

This preliminary operation may take anywhere from 30 to 60 minutes depending on the degree of complexity of the scene and the number of subscenes that are desired.

Subscenes are generally limited to one tape width but two adjacent tapes can be combined to cover areas where specific subjects overlap. Test areas of about 30 x 30 km, selected by scan line and column numbers (pixel address), can be displayed. The scale of the display is approximately 1:100,000. Within this subscene specific test sites (an outcrop, spring, vegetation area, etc.) can be displayed as a window inset at full resolution of approximately 1:28,000 or 1:50,000 scales. Within this inset, a test area of a few pixels can be selected and their radiance values measured and recorded as a histogram for each of the four MSS bands. These are displayed on a separate CRT during the classification analysis process and can be printed on paper by Tektronix printer (Fig. 2).

The histograms display 128 tones or grey levels in LANDSAT bands 4 through 6 and 64 tones in band 7 along the abscissa. The ordinate records the number of "population" of pixels within a grey level or tone having the same radiance values. If the curve is "Gaussian," a narrow, single peak with even equal slopes on both sides of the peak generally indicates that a good signature has been obtained. If two peaks appear, it is considered to be a "bimodal" cluster and is assumed to be a mixed signature of two or more objects. Applying a selected color for the theme to be

extracted, the operator can display the "signature" on the television scene. The theme color can be turned on and off to act as an alarm to call the scientists' attention to specific areas of interest.

RESULTS OF ANALYSIS

A full scene display of the Lake Titicaca image enabled the Image 100 operator and the geologist to study the entire area and define the sub areas to be studied in detail. Three sub areas were selected: The first covers the Tiahuanacu Valley at the southeast end of the lake; the second is located on the north central side of the lake near the Matilde Mining District; and the third is south of the lake where a highly reflective rock (limestone?) crops out over a large area.

First, however, a cursor was used to separate the lake from other water bodies within the scene. The open water area was calculated to be 6763 km² (Fig. 3). Wetland marshes were calculated separately as covering 1152 km². The total lake area and associated wetlands, then, is 7915 km² as compared to earlier measurements of 8100 km² by Brockmann. All bands were used to define reflectance signatures for various parts of the lake, separating deep tones (central lake) from lighter tones (shallows, sediment-laden water) and wetland marshes. An 8-level density analysis of band 4 was run to compare it with the previous step, and similarities were found indicating that band 4 was the major contributor in terms of radiance values by pixel population to the signature analysis (Fig. 4).

In the Tiahuanacu area, wetland marshes (Fig. 5) were separated from sediment plumes (Fig. 6). Vegetation related to ground water effluents and surface moisture were separated by their pale pink tones from other vegetation (red) and dry areas (gray) (Fig. 7). The test area, a grassy region at the base of an alluvial fan, is shown by assigning "white" to pixels within the area. Other pixels, having similar reflectance characteristics, have been alarmed. Those along the north side of the Taraco Peninsula are related to known springs. Grain fields (light blue), located by field observation as stubble in July 1974, were successfully separated from other vegetation and fallow potato fields (Fig. 8).

Most significant for geologists, however, was the cluster analysis and "signature" developed for the outcrop pattern of the Titora Sandstone, a Tertiary formation that is host rock for the Corocoro disseminated copper deposits south of the image area. The test area selected for analysis consisted of about 36 scattered pixels (Fig. 9). The histograms show mean reflectance values of 35, 50, and 55 for bands 4, 5, ^{and} 6 respectively in a total range of 128 gray levels (Fig. 10). Band 7 had a mean reflectance value of 56 in a total range of 64. The extremely low variance values (0.0 - 1.2) indicate a relatively "pure" signature. The test area was then extended to the entire scene (Fig. 11) and resulted in a series of scattered spots conforming well with the suspected outcrop pattern as projected by visual interpretation.

These tentative results suggest that revision of the Geologic Map of South America may be possible through the use of LANDSAT data. In Bolivia the Totora Sandstone is considered to be of Tertiary age while in Peru, rocks of similar reflectance and that appear to be a direct projection of the outcrop pattern from Bolivia have been assigned a Cretaceous age. It is not the intent of this paper to determine which is correct but merely to point out that outcrops having similar reflectance characteristics may be the same formation and should be reviewed by local stratigraphers.

In the Matilde Mine area north of the lake, a search was made for areas of disturbed land which are presumed to be mine dumps. One large area consisting of 36 pixels was identified as the possible location of the Matilde Mine. Using the signature defined, several other areas were "alarmed" which may be smaller areas that have been explored (Fig. 12). Field confirmation of these locations is underway.

An outcrop area south of the lake having high reflectance was studied, because the reflectance seemed to be similar to reflectance values of isolated outcrops of fresh water limestone that occur in the valley north and east of the Taraco Peninsula. Figure 13 shows the outcrop area. The limestone is reported to be similar to limestone that is exploited by a Peruvian cement plant west of the Lake Titicaca scene (Pedro Lavi, personal communication).

CONCLUSIONS

The Image 100 is a highly useful interpretation aid for geologic and other investigations of LANDSAT data. It took approximately 9 hours of computer time to conduct the analyses described in this report. Time can be reduced as the scientist/operator team develops experience in the application of the system. The system can be used for training and planning the most efficient approach to field investigations of rock types. Its greatest use in geologic studies appears to be in the realm of extending and correlating rock types from known to unknown regions. It appears to offer promise in studies of alteration zones related to the occurrence of ore deposits and in subdividing large salars (playa lakes) on the basis of moisture distribution and, thereby, perhaps, mineralogic content by ratioing methods and contrast stretching.

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LIST OF ILLUSTRATIONS

- Fig. 1) Diagram of computer compatible tape (CCT) format showing pixel address of subscenes (1, 2, and 3) by column and scanline numbers.
- Fig. 2) Tektronix printout of CRT display showing reflectance population values of wetland vegetation. Numbers 1, 2, 3, 4, equal Bands 7, 6, 5, 4, respectively. LB denotes "lower boundary" and UB denotes "upper boundary." DEL indicates total gray levels between boundaries. PEAK shows maximum population of pixels in a single gray level. Note influence of absorption by water in narrow gray level display of Bands 6 and 7 (infrared). Vegetation in Band 5 shows bimodal population while Band 4 is "Gaussian."
- Fig. 3) Display of Lake Titicaca showing water area "alarmed" as orange. Wetlands vegetation areas are black.
- Fig. 4) Full density display of Band 4 image of Lake Titicaca enhancing tonal variations. These variations may be related to surface roughness, due to wind currents, sediment load from river effluents, and shallow areas.
- Fig. 5) Tiahuanacu Valley area at southeast end of Lake Titicaca. Taraco Peninsula is at top of scene. Wetland vegetation (totora reeds) is colored orange. Note valley at lower right containing similar vegetation. This suggests that the valley may be an ancient outlet or bay of the lake when water was at a much higher level.
- Fig. 6) Sediment plume (white) of the Tiahuanacu River in Lake Titicaca.
- Fig. 7) Signature display of grassy vegetation believed to be associated with ground water effluent at the base of terrace (right). Enlarged display (left) shows pixel distribution of test area. Spring locations along north side of the Taraco Peninsula (top) were visited during field trip.

Do illustrations accompany this report?

Fig. 8) Vegetation display showing probable grain stubble fields in light blue along north side of Tiahuanacu Valley.

Fig. 9) Outcrop pattern of Totora Sandstone south of Lake Titicaca shown as light yellow pattern. Inset shows detail pattern of test area directly below.

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Fig.10) ^{Tektrenix} Histogram showing reflectance values measured for the Totora Sandstone, south of Lake Titicaca.

Fig.11) Totora Sandstone outcrop pattern (orange) extended to entire scene of Lake Titicaca region.

Fig.12) Maltilde Mine region north of Lake Titicaca showing disturbed ground as bright gray areas.

Fig.13) Limestone area (bright gray) south of Lake Titicaca showing scattered vegetation as bright orange-red.

SMALL-SCALE LANDSAT IMAGE MOSAICS: AN AID TO
PLATE TECTONICS STUDIES

W.D. Carter (EROS Program, U. S. Geological Survey,
Reston, Virginia 22090)
(Sponsor: G.P. Woolard)

The availability of LANDSAT (ERTS-1 and 2) multi-spectral images of most of the land areas of the world provides the geoscientist with an excellent regional view of prominent geologic features. Most geologists have found, however, that single images are not sufficient to include some major structural features and have, therefore, compiled image mosaics of larger areas. Image mosaics of many areas are now available at various scales. Selected areas of the South American Andes have been mosaicked. It is expected that these initial mosaics will stimulate a program that will eventually result in a mosaic of the entire continent of South America.

Preliminary geologic analysis of these mosaics shows rectilinear and curvilinear features, most of which can be correlated with previously mapped or mappable geologic surface features. Lineaments of regional or continental scope may be valid geologic structures, although they generally appear less distinct and are more difficult to confirm by field examination. Many geologists believe them to be related to the presence of deep crustal structures that are reflected through overlying rocks by repeated tectonic activity through geologic time.

Validation of several of these features is underway by field studies and comparison with seismic records, aeromagnetic data, gravimetry, and other geophysical evidence. The possible relationship of continental crustal features to movement of marine plates is drawn for the Nazca subduction zone.

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