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LANDSAT Data: A New Perspective for Geology

A review of the utilization of LANDSAT imagery for geological interpretation.

The LANDSAT (formerly ERTS) satellite program has been in existence for just over two years, and in this brief time has added a whole new dimension to the study of our Earth. Scientists from all over the world have used data measured by LANDSAT's sensors (telemetered down from a 580-mile-high vantage point in space) to monitor pollution and crop growth, explore for minerals and petroleum, and conduct a host of other investigations ranging from animal migration patterns to iceberg monitoring. The mission, originally designed for research and development, has for all practical purposes been considered "operational" from the user's point of view.

To geologists, the regional overview and repetitive coverage of LANDSAT data has been particularly useful, enabling them to take advantage of vegetation and sun angle changes in their attempts to unravel the physical history and setting of the Earth. Successful LANDSAT investigations in geology can be grouped for convenience into four general categories: regional structural studies, geologic mapping, mineral and petroleum exploration, and natural hazards surveys. The categories are arbitrary, and results of investigations might fit equally well into more than one of these.

Abstract: *The* LANDSAT *(formerly* ERTS*) program, while conceived and implemented as a research and development project, has been used as an operational orbital remote sensing system providing data of considerable value to various branches of geology. Areas in which the satellite imagery has been found most useful include regional interpretations of geologic structure, updating and verifying of geologic maps, mineral and petroleum exploration, and the monitoring of natural hazards such as large-scale erosion and seismicity. Investigations in these areas of application demonstrate the wide variety of uses presently undertaken or envisioned for the future. Many benefits have already been felt; others will be seen in the near future where the promise of mineral or petroleum concentration will be realized through conventional ground based and satellite exploration techniques.* LANDSAT *will aid considerably in pinpointing the likely site; "hands on" geology will do the rest.*

Regional Structural Studies

Several investigators studied regional structures and their relationships in LANDSAT imagery, availing themselves of a perspective previously impossible to achieve. Y. Isachsen of New York State's Geological Survey used the 100-by-100-mile images to construct a mosaic of the State and neighboring regions. This mosaic shows, at a glance, geologic relationships of New York State's diverse terrain, major rock units, glacial features, large scale lineaments, and circular structures (Figure 1). Isachsen went into the field to verify the existence of many of these features discovered in the LANDSAT mosaic, and demonstrated how one could use satellite imagery to discern features unsuspected at a larger scale.

Houston and Marrs, LANDSAT inves-

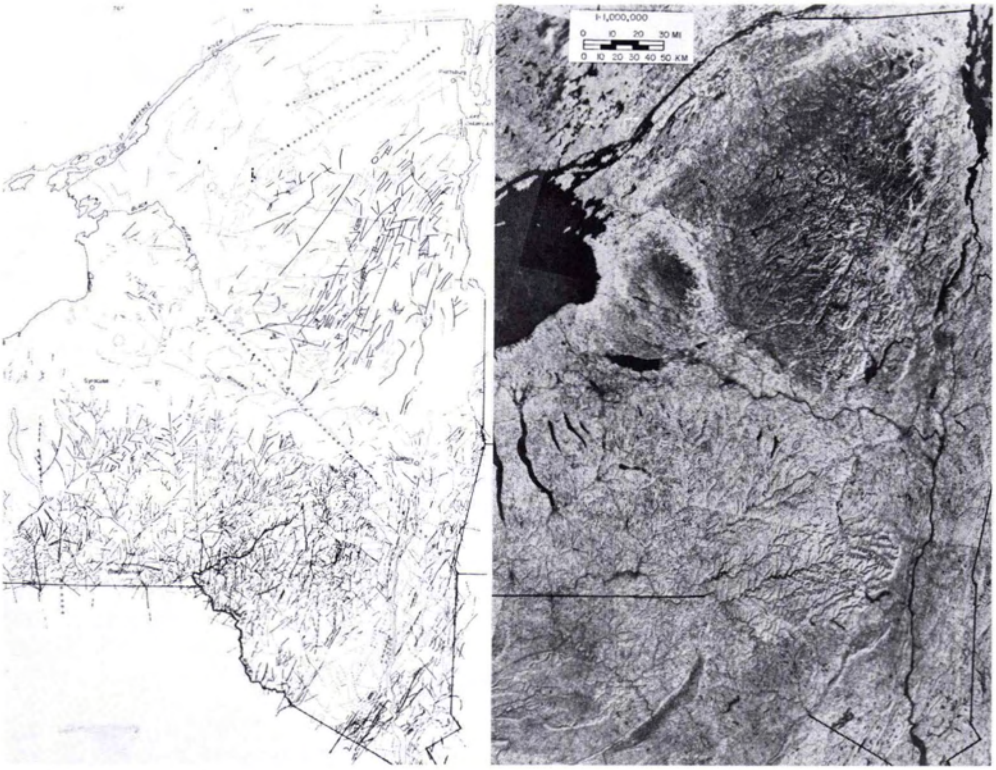

FIG. 1. LANDSAT mosaic and lineament map of eastern New York State (after Isachsen, 1973).

tigators from the University of Wyoming, studied geologic structures in Wyoming by using a LANDSAT mosaic, and reported that their interpretations compared favorably with known ground truth of the region. While this region had been reasonably well mapped by conventional field surveys, the Houston-Marrs study points out the possibility of interpreting poorly mapped regions with a minimum of ground truth, time, and cost with some measure of confidence.

In the East where climate is generally less arid than in some Western States, LANDSAT investigators have still been able to collect valuable geologic information despite the heavier vegetation cover. For example, regional lineaments were discovered and mapped by Gold and co-investigators at Penn State, using LANDSAT imagery of the thickly forested Pennsylvania Appalachians. A private consulting firm has applied computer-aided enhancement techniques (in this case General Electric Company's IMAGE 100 multispectral image processing and display system) to imagery of other areas in eastern Pennsylvania, with success in distinguishing rock outcrops of limited areal extent. Thus, while imagery of arid regions has the obvious advantage of little interference between surface and sensor, investigators have shown that much geological information can be derived from imagery where the ground is obscured by vegetation.

GEOLOGIC MAPPING

The LANDSAT overview and coverage cycle makes map correction and verification a natural application to geology. Investigators H. Blodget and A. Anderson of NASA's Goddard Space Flight Center constructed a three-image mosaic of southern Morocco from which they were able to verify and modify previously mapped lithologic boundaries, and investigate relationships between structural character and mineral emplacement from a regional perspective. A common procedure among LANDSAT investigators has been to use the imagery as base maps upon which geologic interpretations of structure, lithology, and lineament patterns are superimposed. Another team of investigators, M. Abdel-Gawad and J. Silverstein of Rockwell International, discovered that LANDSAT images of Baja and the Gulf of California showed several small islands to have been misplaced on conventional maps, both in geographic location and in topographic detail.

M. Viljoen of South Africa used LANDSAT imagery to unravel the geologic relationships of the South African shield. This investigator was able to distinguish between the granite-gneiss craton, adjacent metomorphic mobile belts, and major "greenstone" intrusions. The nature of these intrusions and their characteristic relationship to the overall geologic setting was recognized by Viljoen to be similar to that found in metallic mineral mining districts in Canada (e.g., Sudbury, Ontario) and Western Australia, and suggests that the South African regions might contain useful concentrations of minerals as well. In this example, the roughly 34,000-square-kilometer region surveyed in a single LANDSAT frame could be broken down into mineralization potential maps with considerable savings in time and cost to mineral exploration interests. On a larger scale, perhaps the most impressive display of LANDSAT's map-making capability can be seen in the mosaic of the 48 conterminous United States, produced by the Soil Conservation Service of the U. S. Department of Agriculture, and available to the public (Figure 2).

Mineral and Petroleum Exploration

The majority of LANDSAT geology investigations fall into this category primarily because of the direct impact on current and projected national needs. Mineral exploration from LANDSAT has been accomplished using the following well-known geologic principles:

- Mineralizing fluids from within the Earth may follow the paths of least resistance to the surface; these paths are zones of weakness through the Earth's crust and occur where the solid rock has been fractured and faulted. Thus, a concentration of "lineaments", many of which can be discerned in LANDSAT imagery, may well indicate where the crust is weakest and, therefore, most likely to be mineralized.
- Some rock types discernible from orbital altitudes are characteristically associated with certain types of minerals because they indicate similar formative conditions or alteration through time.
- Mineralization may alter surface tones by secondary enrichment, vegetation stress and/or chemical changes in the vicinity of the ore body, all of which can indicate that significant mineral concentration has taken place.

Using these and other, more subtle clues, geologists using LANDSAT imagery have reported varying degrees of success in mineral and petroleum exploration studies. Some of these investigators have related LANDSAT-discovered lineaments to known mineral concentrations; many of these studies have been undertaken in the arid regions of Western North America. E. Lathram and other geologists of the U. S. Geological Survey discovered a series of intersecting re-

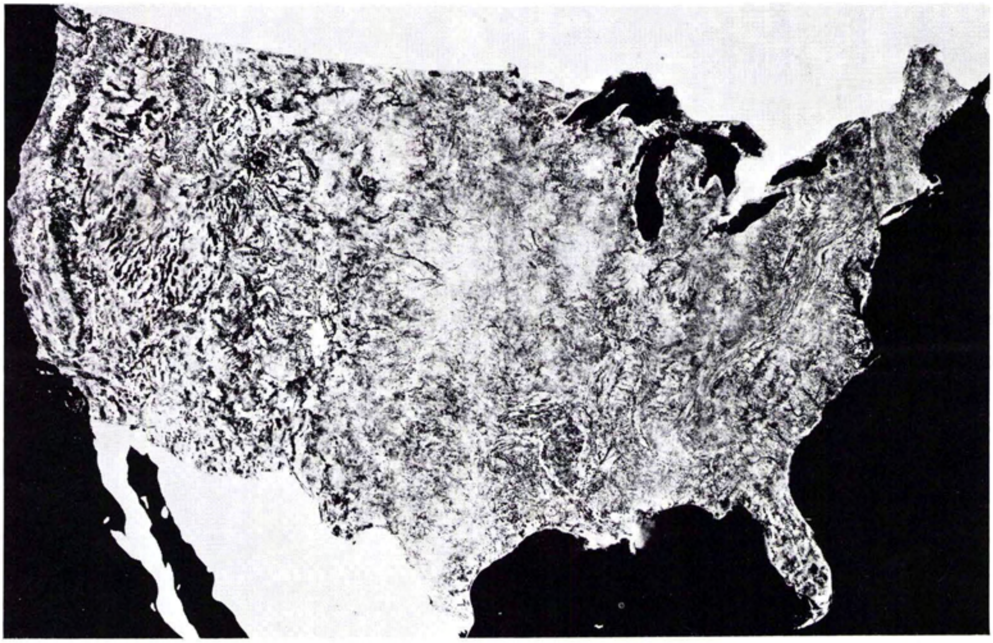

Fig. 2. Mosaic of continental United States compiled from LANDSAT imagery by USDA.

gional lineaments in a rare cloud-free NIMBUS image of Alaska. These lineaments were verified in LANDSAT imagery and enabled the investigators to propose a radically different picture of mineral emplacement in Alaska. Earlier speculation suggested that mineral deposits in Alaska were related to fold belts of the Canadian Cordillera. Based on the occurrence of the newly discovered regional fractures, Lathram and his coworkers suggested that mineral emplacement might also have occurred at their intersections. The result is an alternate hypothesis for mineral emplacement in Alaska, certain to stimulate interest in renewed exploration efforts in areas formerly dismissed as nonproductive (Figure 3).

Further to the south, California investigators E. Rich (1973), Abdel-Gawad, and Silverstein (1973) correlated mining localities with lineaments observed in LANDSAT imagery. Abdel-Gawad and Silverstein, in particular, correlated mercury mining localities with a newly discovered set of transverse faults in the Coast Ranges. The altered serpentine host rock and geologic setting of the mercury ore were non-definitive

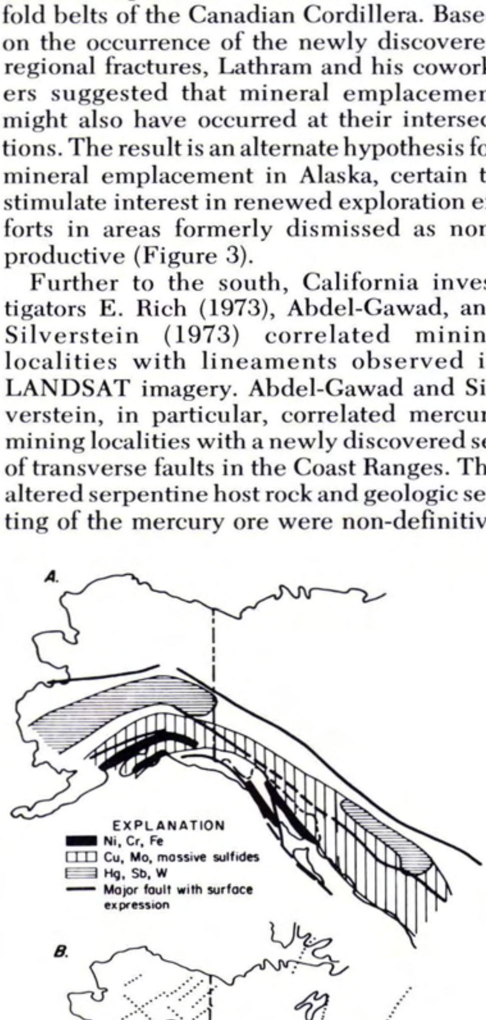

FIG. 3. Projected distribution of selected minerals in Alaska (after Lathram et al., 1973). A. Theory of associaton with geosynclinal evolution of western Cordillera. B. Theory of association with crustal fractures as observed in satellite imagery.

and of little value as ore guides. With the relationship demonstrated by these investigators, future exploration efforts should be simplified markedly (Figure 4). Another Californian, I. Bechtold, demonstrated a similar correlation between tensional fissures in the Lake Mead area (resulting from east-west crustal extension) and concentrations of gold, silver and other metallic ore deposits.

An interesting multilevel geochemical exploration approach was reported by M. Jensen, of the University of Utah, who correlated LANDSAT lineaments with positive aeromagnetic anomalies, and field-checked areas where they coincided. Soil samples were analyzed for mercury vapor, and those areas of highest mercury vapor concentration identified for intensive exploration.

Other investigators have attempted to correlate mineral deposits with characteristic surface tones extracted from LANDSAT imagery visually or by computer enhancement techniques. R. Vincent identified highly oxidized terrain overlying iron ore deposits in the Atlantic City mining district of Wyoming by computer ratioing reflectance values of selected pairs of ERTS bands. The results were analog ratio images, corrected for geometric and atmospheric effects, which showed the oxidation "halos" over the iron ore deposits. A. Goetz and others at JPL developed computer techniques for rock identification and structural analysis in the Colorado Plateau, eventually resulting in the discovery of perched aquifers, ground water sources badly needed by ranchers on the Coconino Plateau of southern Arizona.

LANDSAT data have found application in petroleum exploration as well. Two investigations have met with initial success in this area. E. Lathram in another phase of the study mentioned earlier discovered an unusual regional orientation in a series of lakes on the Alaskan Arctic Coastal Plain. The lakes, generally oval in outline, paralleled regional lineations and deviations in the local gravity and magnetic fields. Supporting ground truth coupled with LANDSAT data led the investigators to postulate the existence of "dip" reversals and regional arching: factors which might indicate potential petroleum accumulation (Figure 5). Similar geologic trends continue to the northeast, and have aroused the interest of the petroleum industry.

Another investigation, headed by R. Collins of Eason Oil Company (Oklahoma City), correlated "hazy" surface tones discovered in LANDSAT imagery of the Anadarko Basin

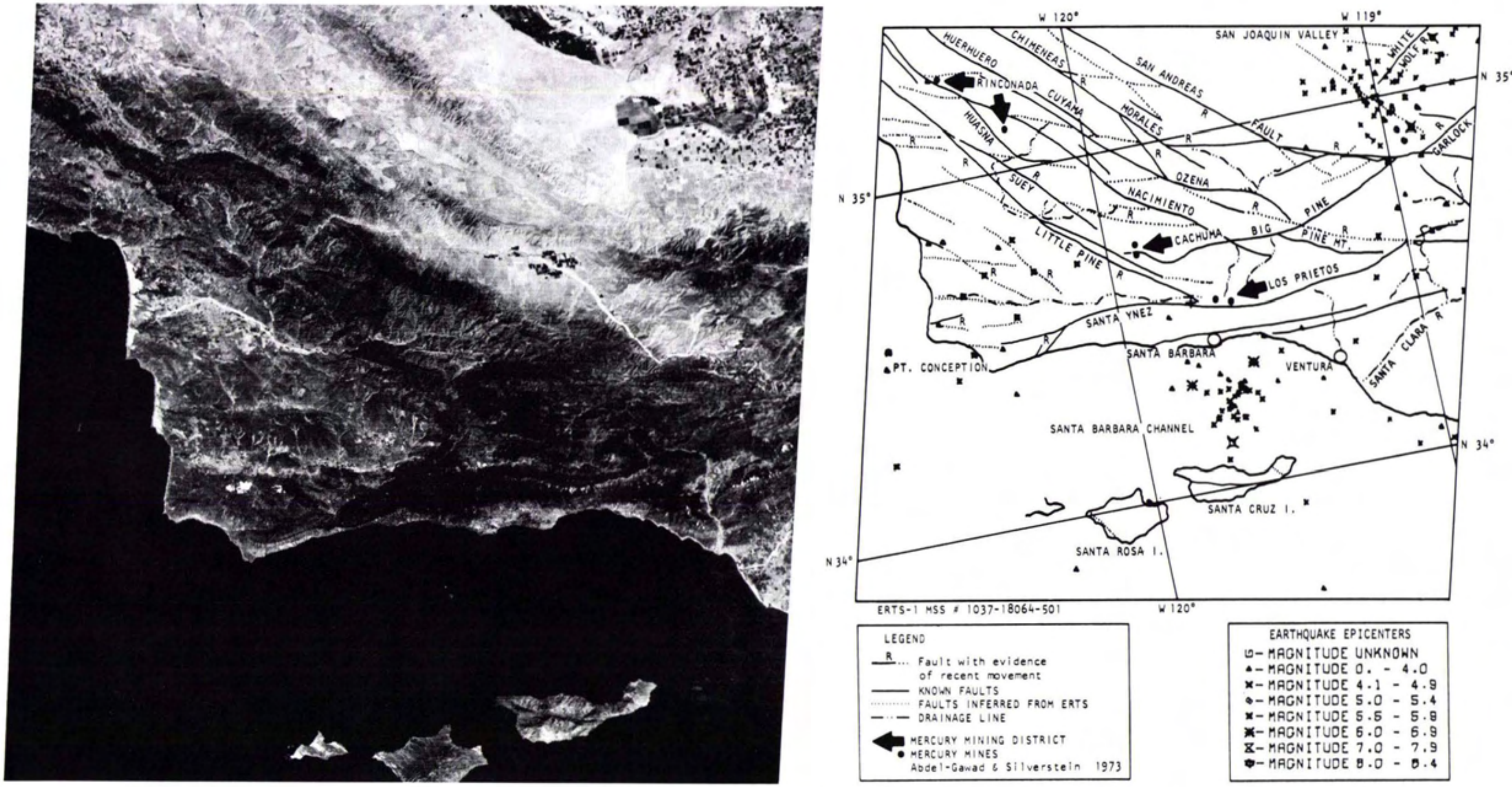

FIG. 4. LANDSAT imagery of southern California and a plot of faults (after Abdel-Gawad and Silverstein, 1973).

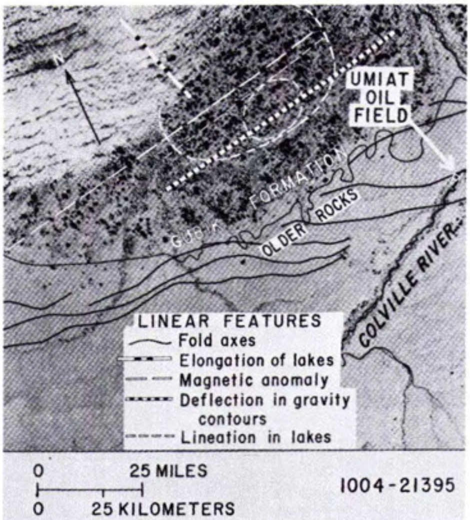

FIG. 5. Lake orientation and associated geophysical lineations on the Alaskan arctic coastal plain (after Lathram et al., 1973).

(NE Texas and SW Oklahoma) with known producing oil fields. Correlation exceeded 85 per cent, and led the investigators to hypothesize that these surface anomalies were the result of volatile components of the petroleum reservoirs migrating to the surface. Whether this phenomenon is a consequence of well drilling or is a natural occurrence remains to be proven.

EARTH HAZARDS: MONITORING AND SURVEYS

Geologic hazards present a direct threat to society in several familiar ways. The catastrophic result of earthquakes and volcanic eruptions, and the less spectacular but equally devastating effects of erosion and flooding can be monitored and better understood through the synoptic and repetitive overview provided by LANDSAT 1 and 2.

LANDSAT investigators have successfully used orbital imagery to inventory, monitor, and even forewarn of potential geologic catastrophes. Among these are USGS geologists Eaton and Ward, who used LANDSAT to relay information from a series of data collection platforms emplaced on active, potentially eruptive volcanoes in Alaska and Central America. DCP instrumentation consisted of seismic event counters and bore hole tiltmeters, both designed to relay data characteristic of the pre-eruptive phase of the volcano. The investigation proved successful when the volcano Fuego, in Guatemala, erupted with devastating force shortly after information relayed from the DCP indicated it would.

Other Earth hazards include the potential of earthquakes in many parts of the world. LANDSAT facilities for locating regional lineaments have been used by investigators dealing with these hazards. M. Abdel-Gawad discovered evidence of recent movement along faults in southern California long considered to be inactive. Seismic hazards maps can be modified by inputs of this type provided by LANDSAT sensors.

L. Gedney of the University of Alaska's Geophysical Institute constructed a mosaic of central Alaska using six LANDSAT images, clearly revealing the presence of sets of "lineaments" (faults and fractures) which correlated well with the distribution of shallow focus earthquake epicenters in the region. Through these studies, an active leg of the Denali fault was found to lie close to a bridge site over the Yukon River, and the proposed route of the Alaskan oil pipeline. Updated seismic data coupled with LANDSAT imagery will enable planners to modify their route selections as necessary.

Perhaps less catastrophic but equally devastating in the long term is the problem of soil erosion. Morrison of the U. S. Geological Survey dealt with regions of accelerated erosion in southern Arizona. Present erosion damage was monitored by LANDSAT, flooding and floodwater recession observed, and an erosion-susceptibility map constructed as an aid to future development.

LANDSAT programs have made significant contributions to many subspecialities within geology. Some of these contributions have already been felt in terms of corrected maps and a more accurate awareness of prevailing seismic hazards.

Some will be felt in the future, where the promise of undiscovered mineral and petroleum deposits can be fulfilled through computer enhancement of LANDSAT data combined with visual interpretation and supporting ground truth.

Data collected by LANDSAT's sensors can provide a wealth of information useful for solving the problems facing man as he tries to live in harmony with his environment. Only thoughtful interpretation of the data, supplemented by the technology of modern computers, will enable him to maximize the benefits "for all mankind."

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Notice

The listing of the Officers of Committees of the Society in the July 1975 Yearbook issue (Page 833) showed A. Trachsel as Chairman of the Publications Committee, whereas L. W. Swanson is, in fact, the Chairman of the Publications Committee.