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ABSTRACT

CONTRIBUTION OF LANDSAT-4 THEMATIC MAPPER DATA TO GEOLOGIC EXPLORATION

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The increased number of carefully selected narrow spectral bands and the increased spatial resolution of Thematic Mapper data over previously available satellite data contribute greatly to geologic exploration, both by providing spectral information that permits lithologic differentiation and recognition of alteration and spatial information that reveals structure. As vegetation and soil cover increase, the value of spectral components of TM data decreases relative to the value of the spatial component of the data. However, even in vegetated areas, the greater spectral breadth and discrimination of TM data permits improved recognition and mapping of spatial elements of the terrain. As our understanding of the spectral manifestations of the responses of soils and vegetation to unusual chemical environments increases, the value of spectral components of TM data to exploration will greatly improve in covered areas.

In areas of well exposed rock such as Death Valley, California, Thematic Mapper data processed to intensity-hue-saturation images provide lithologic discrimination (not identification) sufficient to produce excellent facsimiles to conventional geologic maps with minimal reliance on available data and field checking.

Color composite images of bands 1, 4 and 5 and bands 2, 3 and 4 enlarged to 1:48,000 reveal more than twice as many dikes as 1:80,000 aerial photography and slightly more than the published

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field mapping in the Spanish Peaks area of Colorado. Spectral differentiation, color format, and relatively low angle of illumination all contributed to the recognition of the dikes. In semi-arid areas such as the Wind River and Big Horn Basins of Wyoming, the spectral and spatial resolution of TM data enable clear identification of both the well known northwest trending folds and the less well known "Z-shaped" sigmoidal pattern of left-lateral strike-slip faults that curve to the right into thrust faults. Even in this area of fair soil and vegetation coverage and a light dusting of snow, the iron-staining associated with the Copper Mountain uranium deposits and the anomalous coloration of the Madden gas field stand out clearly.

In the vicinity of Velma, Cement and Chickasha oilfields in southern Oklahoma, where the soils developed on Permian red beds support substantial natural and cultivated vegetation, TM data permit mapping of geological features to a level of detail far beyond that possible with MSS data. Combining information from the satellite image and literature, it appears that Cement Anticline is a "flower" structure developed along a west-northwest trending left-slip fault system. To the east, the fault curves to the right into a north-northwest trending thrust that forms the Chickasha Anticline. South of the Chickasha structure, the fault curves back to the west-northwest orientation and continues to the east-southeast.

As with any tool applied to geologic exploration, maximum value results from the innovative integration of optimally processed TM data with existing pertinent information and perceptive geologic thinking.

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THE CONTRIBUTION OF LANDSAT-4 THEMATIC MAPPER DATA TO GEOLOGIC EXPLORATION

Introduction

The broader spread, narrower band width and better resolution of the new bands and the improved sharpness of the image as a result of the higher resolution all expand the application of Landsat Thematic Mapper (TM) data to geologic exploration. The new data are extraordinarily powerful in themselves. However, their true power is realized when they are imaginatively combined with careful field work and other geological, geochemical and geophysical data in the context of an innovative exploration program held together with perceptive, creative geologic thinking. If the past is any indication of the future, we won't completely understand how to exploit these new data completely for several years. We are still increasing our understanding and ability to apply multispectral (MSS) data more than a decade after the launch of Landsat-1.

Since the early 1960's, the science of geology has been undergoing a major revolution. The new paradigm of plate tectonics and seafloor spreading is replacing the older paradigm of a rigid, stable earth. Inherent in the development of plate tectonic theory is a growing appreciation of the role of plate motion in determining the location of mineral deposits and hydrocarbon accumulations. It is fortunate that developments in spaceborne remote sensing have paralleled these developments in geologic thinking. As a consequence, we have remote sensing tools that view the earth with appropriate scale and scope to enable us to appreciate and map the regional structures that reflect the motions of continent-sized segments of the earth's crust. We received our first glimpses of the earth from space with photos from the Apollo and Gemini flights. The first three Landsat satellites gave us near ubiquitous high resolution (80 metre) coverage of the earth in four spectral bands. These data have had and continue to have enormous impact on all facets of the perception and management of renewable and nonrenewable natural resources and the environment.

In addition to plate tectonics, there is a second revolution going on in the geologic thinking of petroleum exploration. The old paradigm of tightly sealed hydrocarbon traps which retain for long periods of time petroleum that was generated and migrated in the distant past is giving way to an evolving, more dynamic model in which most, if not all, traps leak, and the generation and migration of hydrocarbons is a continuing process. This implies that there is very little, if any, really old oil or gas, rather, only new hydrocarbons generated from old rocks or retained in old traps. The hydrocarbon leaked from these imperfect traps moves vertically through the overlying rocks to the surface and, in the course of its movement, produces a host of chemical changes. The near surface environment manifests this leakage in a variety of geochemical, biological, geobotanical, or geomorphological anomalies and by the simple presence of hydrocarbon itself.

This new paradigm also has important significance to the mineral explorationists. The chemical environment created by leaking hydrocarbon has caused the emplacement of a vast amount of lead, zinc, uranium, and silver and has potentially played a role in localizing some deposits of gold, copper, and barite.

Before considering the impact of the new data types from Landsat-4. let us consider the role data from the first three Landsat satellites have in geologic exploration. In a general sense, Landsat data has made its major contribution to hydrocarbon exploration in the spatial domain. In mineral exploration, Landsat has revealed some spectral information, but again the major contribution is spatial. The synoptic view of over 34,000 square kilometres of the earth's surface on a single Landsat image permits the detection and mapping of major regional structures associated with the geologic development of entire geologic provinces. It is also possible, through special digital enhancements, to map some of the more subtle surface expressions of fracturing, folding and alteration associated with hydrocarbon accumulations and the emplacement of mineral deposits. The data make it possible to interrelate widely separated geologic features and detect subtle changes that occur over tens of miles and, hence, have gone unnoticed on conventional types of data. Perhaps most important of all, the new perspective that the view from space provides stimulates us, even forces us, to think of geology in new ways and perceive new possibilities. It is an extremely powerful tool. It has not by itself "found" an oil field or mine, but it has made significant contributions to the exploration thinking that led to the discovery of millions of barrels of oil and millions of tons of ore.

The two major advantages of Thematic Mapper data over that of the MSS system are its increased spatial resolution and its greater number of narrow, strategically placed spectral bands. The 30-metre pixel size will permit finer definition of ground features and thereby improve the reliability of photo-geologic interpretation of geologic structure. Of equal importance is the increased homogeneity of the type of surface material within a given pixel. The less mixed the pixel, the greater the potential of extracting useful spectral information. The increased spectral resolution is allowing geologists to map altered zones associated with mineralization based not only on iron oxides, but on the basis of recognizing rocks and soils rich in hydroxyl groups, such as many of the clays formed as a product of the mineralization process.

The increased spectral sensitivity also promises the ability to detect some types of vegetation changes that are associated with anomalous mineralization. This will be particularly helpful where soil and plants obscure the bedrock. This capability is not definitely proven, but it is theoretically possible and highly anticipated.

All of the above implies that digital processing techniques will play a much greater role in the application of TM data to exploration than it has in the application of MSS data. One of the lessons we relearned many times while using MSS data is that there is no single process that is appropriate to all areas or to all applications. Processing must suit the application and the area. Processing of TM data must be even more finely tuned to purpose and environment that that for MSS data.

In general, the value of the spatial data increases relative to the value of the spectral data as soil and vegetation cover increase. However, even in covered areas, the increased spectral sensitivity contributes to interpretation by making the spatial elements of terrain fractures, geomorphology, etc., more easily recognizable. One factor that aids interpretation immensely is 30-metre resolution, so that the digitally processed images easily stand enlargement to 1:50,000 and, in some instances, larger scale - a capability that greatly reduces uncertainty, ambiguity and error in interpretations.

Death Valley, California

In arid areas with good exposure, such as Death Valley, California, it is possible, with careful digital processing, inventive color compositing, to produce enough spectral differentiation of rock types so that it is possible, using standard photo interpretation techniques, to produce facsimiles of standard geologic maps with a minimum of field work or reference to existing maps. The match isn't perfect but it is much better than that possible with the MSS data. Compare Figure 1, a portion of the 1:250,000 scale geologic map of Death Valley (1977) produced by the California Division of Mines, to Figure 2, the generalized geologic map produced from an intensity-hue-saturation TM image. Intensity-hue-saturation, or IHS. is one of the more exciting new combinations possible with the TM data. Through the use of two ratios to control hue and saturation, and the first eigen band as the intensity, the resulting IHS image possesses the spectral information of a ratio image and the spatial integrity of the first eigenband. The hue of the image is controlled by the ratio of TM5 (1.6 microns) over TM2 (0.56 microns). The color assignments are such that high ratio values are red with decreasing values passing through the spectrum ending with the lowest values in blue. The saturation of the image is controlled by the ratio of TM5 (1.6 microns) over TM7 (2.2 microns).

TM2 was chosen for its sensitivity to ferric iron oxides; TM7 for its sensitivity to hydroxyl bands and TM5 for its high variance and broad information content. The 5/2 ratio will have high value (red hue) over areas of high ferric iron content, vegetation, as well as an assortment of other surface materials. The 5/7 ratio will have particularly high values (high saturation on the output image) over areas which contain hydroxyl bearing minerals or surface materials containing free water (e.g., clays, hydrated salts and vegetation). The first eigenband presents a positively weighted sum of the seven TM bands and thus provides excellent geomorphologic information allowing for precise geographic locations of the image's spectral information.

Four Corners Area

In a slightly less arid area, such as the Paradox Basin of Utah and Colorado, soil cover and vegetation are much better developed than in the Death Valley. We have not yet had an opportunity to examine TM data from this area, but we know from Thematic Mapper simulator (TMS) data that digital processing can enhance spectral signatures even where the surface is 20-50% covered with vegetation. Of particular interest are the well known "bleached" red beds associated with uranium deposits and hydrocarbon accumulations. Probably the best known examples are on the southwest flank of Lisbon anticline where the Triassic Windgate sandstone, which is normally a warm rosy brown cliff-forming rock unit in the area, is bleached almost white in the vicinity of uranium and hydrocarbon deposits. Uranium explorationists have used this bleaching of red beds as an exploration indicator for many years.

There is a growing body of evidence that there is more than a coincidental association of hydrocarbon and uranium in many localities. The general theory is that hydrocarbon escaping from reservoirs in small quantities over long periods of time acted as reductants that helped precipitate uranium from laterally moving groundwater, reduced and mobilized red hematite cement, and reprecipitated the iron as sulfides, which revert to hydrated iron oxides when exposed to oxidation in the course of erosion. Indeed, the "bleached" rocks contain "limonite" concretions and the laterally equivalent rocks do not.

Several processing techniques highlight these color differences in TMS imagery. The differences are visible in "natural" color composites (TMS bands 1, 2 and 3) and in other more exotic processes, particularly those involving ratios (e.g., 4/3, 1/3, 7/5).

The question then is, can recognition of these color anomalies act as exploration guides? The answer, of course, is sometimes yes and sometimes no. Obviously, not all hydrocarbon accumulations, or uranium deposits for that matter, occur in areas with red beds that are susceptible to bleaching at the surface. Further, in many areas with red beds at the surface, vegetation and soils are so extensive as to mask even the most blatent anomalies. Clearly, we must modify our exploration approach to suit the conditions at hand. Work is underway to recognize subtle differences in carbonate and clay mineral distribution that are known to result from hydrocarbon seepage. An even more challenging task is to understand and reorganize the changes in plants and soils that microseepage produces.

Spanish Peaks, Colorado

The Spanish Peaks area of south central Colorado offers a striking example of the contribution that TM data can make to exploration. The area is a Cretaceous to early Tertiary basin that was deformed and uplifted in Eocene time. It was the locus of several episodes of intrusive activity during Miocene time that produced the spectacular volcanic necks that form the Spanish Peaks and the complex dike pattern. Interpretation of a color composite composed of TM bands 1, 4 and 5 (Figure 3) enlarged to 1:48,000 revealed more than twice as many dikes as 1:60,000 scale black-and-white aerial photography. The number, location and distribution of the dikes compare very favorably to detailed field mapping of the area. In particular, dikes mapped on the TM imagery tend to be longer than those on the field map, and the field map reveals a few dikes not seen on the TM imagery. This type of information is useful, if you are trying to avoid drilling volcanic rock in the course of petroleum exploration. Spectral differentiation, color format, regional perspective and image continuity and low angle of illumination all probably contributed to recognition of the dikes in the area.

Big Horn and Wind River Basins, Wyoming

The Big Horn/Wind River Basin area of Wyoming lies just east of the Overthrust Belt in the area of foreland deformation (Figure 4). The area has more soil development and vegetation than the previous two areas. The light dusting of snow over the area in available TM data effectively frustrates spectral work.

Regional interpretation of the Overthrust Belt reveals several recurrent patterns of structural features portrayed in a highly generalized fashion in Figure 5. In particular, we noticed that the WNW trending left-slip faults curve to the right into thrusts and northeast trending right-slip faults curve to the left into thrusts. The thrusts curve either to the left into left-slip faults or to the right into right-slip faults. This yields three basic patterns: "Z" shaped left-slip thrust left-slip; "S" shaped right-slip thrust right-slip; or concave westward left-slip thrust right-slip patterns. These same patterns extend into the foreland in a less compressed form.

A color composite of TM bands 1, 4 and 5, a combination that, by one set of calculations, contains the greatest amount of information available from a single three-band combination, reveals many of the structural and stratigraphic features better than either natural color (1,2,3) or false color infrared (2,3,4) versions. Despite the snow, one can see some peculiar coloration over the Madden gas field and the Copper Mountain uranium deposits.

Based on a quick interpretation (Figure 6), the structure in the Owl Creek area looks like some of the structures to the west. The major thrust on the south side of the Owl Creek Range is well known and parallels the thrust in front of the Wind River Range to the south. The strike-slip faults are less well known.

One possible exploration for the occurrence of uranium at Copper Mountain is that uranium in groundwater moving downward along the frontal strike-slip fault system was reduced by methane moving upward and out of the basin along the same fault zone. In the Overthrust Belt to the west, we observed that virtually all the hydrocarbon discovered to date occurs in the transition zone where thrusts are becoming strike-slip faults. These two general exploration models make several areas in the Big Horn/Wind River intriguing exploration targets.

Cement-Velma, Oklahoma

In the more humid and agriculturally stirred areas, the role of spectral data tends to diminish. Just as Goldfield, Nevada is the Olympic training grounds for MSS spectral signatures of hydrothermal alteration, the area around Cement, Oklahoma is possibly the best documented instance of surficial alteration related to microseepage of hydrocarbons. Terry Donovan (1974) found a variety of chemical anomalies at and near the surface and Jerry Furgeson (1979) found anomalous amounts of pyrite in the Permian rocks of the subsurface. Vegetation is relatively dense, though much of it was dead at the time TM data were acquired. On the ground, alteration in the form of bleached red beds, anomalous calcite cement, ironstone concretions, etc., is obvious. To date, none of the digital approaches we have tested (ratios, compound ratios, principal components, IHS. etc.) has reliably indicated a credible anomaly. There are a few areas that show a bit of a bluish tinge in the 1,4.5 imagery. Some of these areas do correspond with structural culminations and some of Donovan's geochemical highs, but they are subtle, feeble, and open to a wide variety of interpretation.

In contrast to the spectral data, the structural data are mildly spectacular. Leo Herrmann's 1961 version of the structure on the Deese group at 5,000+ feet and beneath the Permian unconformity (Figure 7) matches rather well with a simplified version of the features that can be interpreted from a 1.4.5 image of the TM data. Again, there is the same "Z" shaped configuration of WNW trending left-slip faults and north trending thrust faults we saw in Wyoming. Cement Field is located on a "flower" structure along a left-slip fault and Chickasha Field is on the related thrust fault. The Velma Field is located further to the southeast along the same left-slip fault that controls Chickasha field. Examination of the image reveals several similar but untested structures. These, of course, should be examined in detail. In addition, we need to spend more time looking for subtle geochemical and geobotanical effects.

Summary and Conclusions

As with any tool applied to geologic exploration, maximum value results from the innovative integration of optimally processed TM data with existing pertinent information and perceptive geologic thinking. There is a serendipitous parallel development of satellite remote sensing with the concepts of plate tectonics and vertical migration of hydrocarbons. Conjunction of the new technology and new paradigms allows the effective, rapid examination of large areas for indications of exploitable resources. The synoptic view of the satellite images and the relatively high resolution of TM data allows us to recognize regional tectonic patterns and map them in substantial detail. The refined spatial and spectral characteristics and digital nature of the Thematic Mapper data permit detection and enhancement of signs of surface alterations associated with hydrothermal activity and microseepage of hydrocarbons that have previously eluded us.

In general, as vegetation and soil cover increase, the value of spectral components of TM data decreases with respect to the value of the spatial component of the data. This observation reinforces the experience from working with MSS data that digital processing must be optimized both for the area and for the application.