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

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Thank you, Mark (Chair).

Today, I'm going to chat with you about the spectacular Landsat-4 TM data and the contribution it is making to geologic exploration. I don't know what your initial reaction was to the broader spread, narrower band width and better spectral resolution of the new bands and the incredible sharpness of the image as a result of the higher resolution. Quite frankly, I was pleasantly flabbergasted and that secret little voice in my head said, "Hey, you hardly have to think anymore. All you have to do is sit at the console and twiddle the knobs till the lithology, structure, geochemical anomalies, vegetation signatures, etc., spread across the screen in vibrant living color. Then lease, stake, drill, and let the good times roll." We explorationists are eternal optimists. Seriously, that dream passed in a flash, but I think all of us were initially mesmerized by the power of the potential spectral differentiation that the new data held out. The new data are extraordinarily powerful in themselves. However, their true power is realized when they are

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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 do this for several years, but the prospect is delightful.

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 acceptance 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 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 non-renewable 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 a newly evolving paradigm which envisions a much more dynamic scenario 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's take a look at 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. Truly it isn't a panacea but 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 types 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.

During the remainder of our chat, I'd like to share some examples of how TM data can contribute to geologic exploration. 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 helps a great deal is 30 metre resolution, so that the digitally processed images easily stand enlargement to 1:50,000 and, in some instances, larger scales. A great improvement over the 80 metre pixel of MSS data.

In arid areas with good exposure, such as Death Valley, California, it is possible with careful digital processing and some inventive color compositing, to produce enough spectral differentiation of rock types so that it is possible to produce facsimiles of standard geologic maps with a minimum of field work or reference to existing maps. The match isn't perfect, as you will see, but it is pretty good - much better than with the MSS data.

These images you all probably recognize as natural color (bands 1, 2 and 3) on the left screen and false color infrared (bands 2, 3 and 4)

on the right screen (part of a TM scene acquired 17 November, 1982). The false color infrared clearly does a better job of lithologic differentiation, but a lot of geologic features are visible on both images, such as the Furnace Creek fault zone, the various facies, and the Cambrian marine rocks in contact with the Precambrian metamorphic rocks and Tertiary rhyolites.

LEFT: HSV

RIGHT: Geol. Map

On the right is a geologic map of the area not a TM image. On the left is a Hue-Saturation-Value or HSV image, one of the more exciting new combinations possible with the TM data. Through the use of two ratios as hue and saturation, and the first eigenband as the value, the resulting HSV 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 represents 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.

You can see there is a pretty good comparison of this image with the 1:250,000 scale Death Valley sheet of the Geologic Map series of California. Through comparison with the geologic map, some interesting examples of the unique information content of the HSV image appear along the northeastern flank of the Panamint Mountains, the eastern Funeral Mountains and the northern portions of the Resting Spring Mountains. The lower Paleozoic marine section along the northeastern flank of the Panamints is clearly distinguished from the older (PC?) section to the west. The small outcrops of Tertiary volcanics overlying the Paleozoic section are also clearly distinguishable. Note, however, that the Paleozoic marine section to the north (Tucki Mountain area) is spectrally "confused" with the Tertiary volcanics. The Tucki section is distinctly different from the Paleozoic sediments to the south of Black Water Wash, however, it is not immediately clear why its 5/2 ratio should be so spectrally similar to that of the Tertiary volcanics. In the marine Cambrian rocks of the Panamint Mountains, there are several examples of stratigraphic horizons which are clearly mappable on the HSV imagery and have been grouped into the Cambrian marine unit on the 1:250,000 scale geologic map. Although such groupings are obviously necessary during geologic mapping, the ability to map the individual lithologic beds on the HSV imagery significantly augments the information available on the geologic maps.

The alluvial fans are conspicuous and it is possible to distinguish several ages of fans. It is interesting that the colors of several of the fans relate to their provenance. On the interpretation, the fans are brown, blue, green and red - oldest to youngest.

LEFT: Wyoming Geological Map

RIGHT: Overthrust Regional

Moving eastward to an area with more soil development and vegetation, let's take a look at the Big Horn/Wind River Basin area of Wyoming. The area lies just east of the Overthrust Belt in the area of foreland deformation as indicated on the map on your left.

In looking at the Overthrust Belt during a regional interpretation project, we found several recurrent patterns of structural features portrayed in a highly generalized fashion by the map on your right. 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. In the Wyoming Overthrust, the concave sheaves of thrust faults are the most obvious pattern, as you can see. These same patterns extend into the foreland in a less compressed form.

LEFT: 2,3,4 Owl Creek

RIGHT: 1,4,5 Owl Creek

On the left is the standard infrared version of the TM scene of the Big Horn/Wind River Basin acquired Nov. 21, 1982. On the right is a composite of 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. Isn't that turquoise snow lovely! However, it really frustrates detailed spectral work. There is some peculiar coloration here over the Madden gas field. Both versions let you do a pretty good job of mapping structure based on the orientation of bedding, but I think you'll agree the 1,4,5 image has the edge. Clearly, there is a problem here where two sets of bedding meet at a substantial angle.

LEFT: Kemmerer Scene with Overlay

RIGHT: 1,4,5 with Overlay

Based on a quick interpretation, the structure in the Owl Creek area looks like some of the structures to the west. The major thrust 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 explanation 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.

Another interesting aspect is that, in the Overthrust, we observed that virtually all the hydrocarbon discovered to date occurs in the transition zone where thrusts are becoming strike-slip faults. That makes similar areas in the Big Horn/Wind River area quite intriguing.

LEFT: Cement 2,3,4

RIGHT: Cement 1,4,5

As we move into the more humid and agriculturally stirred areas, the role of spectral data tends to diminish. This is the area around Cement, Oklahoma. Just as Goldfield, Nevada is the Olympic training

grounds for MSS spectral signatures of hydrothermal alteration, Cement 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. The vegetation is pretty dense, though much of it is dead, and I'm here to tell you it is tough to see a spectral anomaly that comes close to the surface geochemical anomalies in any of the massaging of the image we've done. The fact that the false color infrared image on your left doesn't have a pervasive yellow cast as a consequence on all the red soil usually present in Oklahoma is a bit anomalous in itself. There are a few areas that show a bit of a bluish tinge in the 1,4,5 image on your right. Some of these areas do correspond with structural culminations and some of Terry's geochemical highs, but they are pretty subtle or feeble.

LEFT: Structure on Deese

RIGHT: 1,4,5 Overlay

Fear not, all is not lost. The structural data is mildly spectacular. On the left is Leo Herrmann's 1961 version of the structure on the Deese group at 5,000+ feet and beneath the Permian unconformity. On the right is the 1,4,5 image with a simplified version of the features that can be interpreted from the TM data. Again, we see 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. A number of other fields, such as Uchna, Gotebo, Broxton and Apache, along the Amarillo-Wichita Mountain front are located on similar structures. 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. This is certainly one of the best documented test sites for looking for geochemical anomalies.

LEFT: Detroit 2,3,4

RIGHT: Detroit 2,3,4 Overlay

As a final example, let's look at an area where the value of the TM data is almost entirely spatial, two reasons being that we only have bands 1 through 4, and the area is very heavily vegetated.

In the vicinity of Detroit, thick glacial soils cover bedrock and support verdant vegetation. The spatial resolution of TM data permits one to distinguish glacial surficial features from fractures that have propagated through the overburden from the underlying bedrock. Most of the Ordovician Trenton-Black River oilfields, and many of the Silurian and younger "reef" fields in the area, are related directly or indirectly to fractures. Several lineaments that appear to be coincident with fractures known in the subsurface stand out well on TM imagery of the area.

TM FCC OF SOUTHERN ONTARIO

On the false color image of the Ontario area, we have delineated some of the more prominent linears along with the location of the Malden, Colchester and Leamington oil and gas fields. At the Malden and Colchester fields, the hydrocarbon accumulations are in fractured, dolomitized, Ordovician limestones. The fractures trend WNW. It's a safe bet that

the lineament marked on the imagery is the surface expression of a major through-going structure which is controlling the subsurface fracturing.

The Leamington field is a little younger and is located in reef deposits. Reefs prefer the high edge of structural blocks. The intersecting lineaments mapped on the imagery may well mark intersecting normal faults responsible for the slight uplift of a block edge and the localization of the Silurian reef.

As you are probably aware, the largest field in Michigan is the Albian-Scipio trend -- a fracture-controlled accumulation. A number of the recent discoveries in Michigan, including the Dart-JEM discovery, are also fracture-controlled. Clearly, data from TM can play a very large role in this type of exploration play.

It might be useful to know all of the TM imagery we looked at is 1:100,000 scale except for the images of Detroit, which are 1:250,000.

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. The conjunction of the new technology and new paradigms allow 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.

Thank you for your patience and attention. I'll be glad to answer almost any question.