Successful Use of Landsat Thematic Mapper Data for Mapping Hydrocarbon Microseepage-Induced Mineralogic Alteration, Lisbon Valley, Utah

Donald B. Segal
Tydac Technologies Corporation, 1655 North Fort Myer Drive, Suite 320, Arlington, VA 22209
Ira S. Merin
Io Geological Consultants, 3041 White Birch Court, Fairfax, VA 22031

ABSTRACT: Lisbon Valley, Utah, is an area of considerable interest to exploration geologists because of the spatial correspondence between subsurface hydrocarbon accumulations and uranium mineralization, and the presence of bleached (mineralogically altered) rocks of the Wingate Formation on the surface. Three mineralogically different types of Wingate Formation are present within the study area, including unbleached rocks and two types of bleached rocks, one of which is uniquely associated with the underlying hydrocarbon accumulation and uranium mineralization. Unbleached rocks have abundant ferric-iron and relatively small amounts of kaolinite. Bleached rocks not associated with underlying hydrocarbon reservoirs lack ferric-iron and have moderate amounts of kaolinite. Bleached rocks that overlie the hydrocarbon accumulation at the Lisbon Field also lack ferric-iron, but contain a relative abundance of kaolinite.

A detailed analysis of Landsat Thematic Mapper (TM) data was undertaken in order to evaluate its potential for distinguishing the three mineralogically different types of Wingate Formation present at Lisbon Valley. The results of this study demonstrate that Landsat TM data can be successfully used to map spectral variations that have a direct correspondence with hydrocarbon microseepage-induced mineralogic alteration at Lisbon Valley. Because of its widespread availability, synoptic coverage of large areas, and sensitivity to small variations in iron and clay mineral composition, the extrapolation of these results may have profound implications for mapping microseepage related mineralogic alteration in other areas of exploration interest.

INTRODUCTION

LANDSAT DATA are extensively used for sedimentary basin evaluation and hydrocarbon exploration in a wide variety of ways. Most previous studies have utilized the synoptic, regional perspective provided by satellite imagery for structural and stratigraphic interpretations and have focused primarily on the spatial attributes of the multispectral data, utilizing enhancements of the spectral information to provide improved spatial discrimination.

Within the last several years the concept that many hydrocarbon traps are indeed not perfectly sealed, and that, throughout geologic time, leakage of fluids can result in the alteration of surficial materials, has gained considerable acceptance. Coincident with the development and refinement of this theory, data from satellite-borne remote sensing systems have become available that enable discrimination of subtle variations in surface composition that are not visible to the naked eye. Lisbon Valley, Utah, is one such area where the microseepage of hydrocarbon-related fluids has resulted in the development of mineral alteration assemblages that are only resolvable by exploiting the spectral information present in the near-infrared wavelengths.

Lisbon Valley is a northwest-trending anticline located in southeastern Utah (Figure 1). The Wingate Formation is exposed along the southwestern flank of the anticline. The Wingate is a Triassic-aged, thick-bedded, erosionally resistant sandstone that is normally red-colored due to the abundance of ferric-iron as a cementing agent. However, at Lisbon Valley two distinct areas of bleached Wingate are present. Lisbon Valley is the site of one of the largest hydrocarbon accumulations in Utah and is also known as a major producer of uranium, which occurs in strata that underlie the Wingate Formation. Figure 2 is a map showing the distribution of bleached and unbleached exposures of the Wingate Formation, uranium mineralization, and hydrocarbon production at Lisbon Valley (after Conel and Alley, 1985).

FIG. 1. Map showing the location of Lisbon Valley, Utah.

Numerous "dry" holes were drilled on the crest of the surface anticline before it was realized that the subsurface structure, which acts as a trap for the hydrocarbons, is actually offset to the southwest. The axis of this subsurface structure directly underlies the surface dip-slope of the Wingate Formation. The gases in the Lisbon Field reservoir are know to contain relatively large quantities of carbon dioxide (CO_2) and hydrogen sulfide (H_2S), which are strong reductants and can also be acidic (Wood, 1968). Previous research has suggested that hydrocarbon microseepage may account for the close spatial correspondence between the bleached Wingate and the presence of uranium mineralization in the rocks that overlie the Lisbon Field reservoir at Lisbon Valley (Conel and Niesen, 1981; Conel and Alley, 1985).

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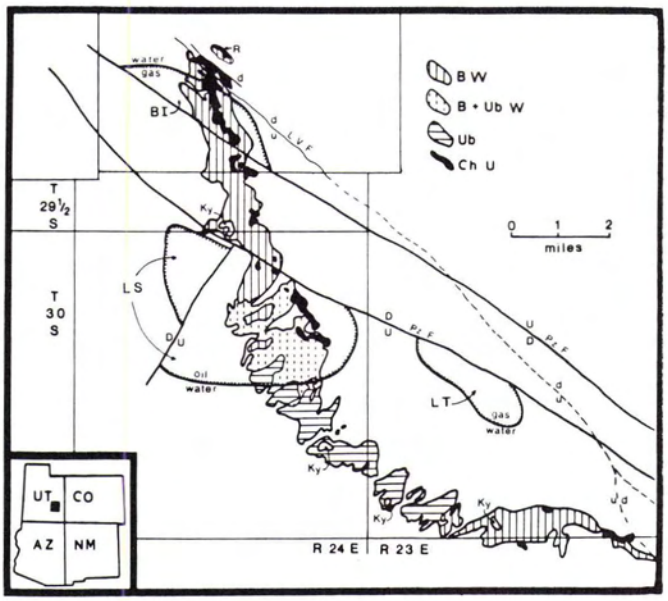

FIG. 2. Map showing the distribution of bleached and unbleached exposures of the Wingate Formation, uranium mineralization, and hydrocarbon production at Lisbon Valley, Utah (after Conel and Alley, 1985). The distribution of erosional remnants of the overlying Kyenta Formation (Ky); outcrops of bleached Wingate (BW), unbleached Wingate (Ub), and mixed bleached and unbleached Wingate (B + UbW); uranium ore bodies in the Chinle Formation (ChU); and the limits of the Lisbon Field (LS), Big Indian Gas Field (BI), and Little Valley Gas Field (LT) are indicated. The Lisbon Valley Fault (LVF), as well as several subsurface faults (PzF), are also shown.

HYDROCARBON MICROSEEPAGE

Surficial evidence of oil and gas seepage has long been used as an exploration tool in the search for subsurface hydrocarbon accumulations. Although there are a wide variety of possible mainfestations of hydrocarbon-induced alteration, many anomalies are directly related to an essential premise: Leaking hydrocarbons and associated fluids promote the development of a reducing environment, thereby initiating diagenetic (post-depositional) Eh/pH-controlled chemical reactions in the strata that overlay the leaking reservoirs. These mineralogic changes may, in turn, promote geomorphic, geobotanical, or other physical alteration of the surface and near-surface strata that can be detected using remotely sensed data. Research concerning the detection of mineralogic changes caused by microseepage-induced alteration phenomena is currently at the forefront of geologic remote sensing for hydrocarbon exploration.

BLEACHING OF REDBEDS

Anomalous coloration of exposed rocks overlying hydrocarbon reservoirs has been noted by numerous authors (Donovan, 1974; Ferguson, 1979; Conel and Niesen, 1981). In unaltered redbeds, the red color is typically caused by the presence of ferric-iron in hematite, geothite, or other limonitic minerals (Walker, 1967). Ferric-iron bearing (limonitic) minerals are stable in oxidized environments and are soluble under reduced or acidic conditions. Thus, where redbeds have been affected by microseepage, the ferric-iron is converted to the ferrous state and is either re-precipitated as ferrous compounds or dissolved, leaving the rock with a bleached coloration. Limonitic and nonlimonitic rock types can be readily discriminated using relatively broad-band visible wavelength spectral remote sensing systems such as the Landsat Multispectral Scanner (MSS) or the Thematic Mapper (TM).

URANIUM MINERALIZATION

In many areas, uranium mineralization and the presence of other radioactive compounds tends to be associated with petroleum accumulations. In general, the geochemical behavior of uranium is essentially opposite that of ferric-iron. Uranium is soluble in oxidizing conditions and is insoluble in its reduced state. Thus, reducing conditions, such as those caused by the presence of hydrocarbons or H_2S, favor the precipitation of uranium minerals.

At Lisbon Valley uranium mineralization is present in the northern and southern portions of the southwestern flank of the anticline in two distinct geologic units (Wood, 1968; Weir and Puffett, 1981). In the Chinle Formation, which directly underlies the Wingate, the uranium ore consists of primary unweathered reduced minerals that were emplaced during Triassic and Jurassic times. In the Cutler Formation, which underlies the Chinle, the uranium ore consists of secondary weathered and oxidized minerals that formed later during late Cretaceous and Eocene times. The Cutler ore is thought to have formed from oxidative weathering of the overlying Chinle deposits, which led to a redistribution of the uranium from the Chinle to the Cutler (Reynolds *et al.*, 1985).

The most likely mechanism for localizing the Chinle ore is that laterally moving metal-rich fluids encountered strata containing reductants (e.g., methane or H_2S) that were derived from degradation of *in situ* carbonaceous material and/or from upward migration of fluids from a petroleum reservoir. Wier and Puffett (1981) note that, in many mineralized portions of the Chinle, primary carbonaceous materials remain unaltered. Because the relationship between the organic material and the ore is not clear, the geographic proximity of the ore to the hydrocarbon accumulation at the Lisbon Field is suggestive of a microseepage-derived reductant.

CLAY MINERALIZATION

The chemical environment resulting from hydrocarbon microseepage may induce diagenetic alterations that can modify the distribution, relative proportion, and composition of clay minerals present in the strata that overlie a leaking reservoir. Leaking fluids commonly contain quantities of CO_2 or H_2S sufficient to be slightly acidic. Acidic solutions cause certain minerals, such as feldspars and clays that are stable in basic environments, to be altered and replaced by other clay minerals. Many clay minerals exhibit diagnostic absorption features in the near-infrared (2.0- to 2.5-micrometre) wavelength region (Hunt and Salisbury, 1970; Hunt *et al.*, 1973; Hunt, 1977). Laboratory reflectance curves for various clays are shown in Figure 3. Although the breadth of the Thematic Mapper bands precludes unique clay mineral identification, distinctions between certain types of clay minerals and/or relative quantities of clay minerals is possible with TM data.

PREVIOUS RESEARCH

Recent studies of the effects of hydrocarbon microseepage on the Wingate Formation at Lisbon Valley have utilized aerial photography, Landsat MSS data, and airborne spectroradiometric data in conjuction with detailed mineralogic determinations, thin-section analyses, and laboratory reflectance spectra (Segal *et al.*, 1984, 1985, 1986; Merin and Segal, in press). The results of these studies have shown that three mineralogically different types of Wingate Formation are present within the study area, including unbleached rocks and two types of bleached rocks, one of which is uniquely associated with the underlying uranium mineralization and hydrocarbon production.

Although the degree of bleaching (ferric-iron loss) is similar in both bleached areas, detailed analyses have shown that there is a strong correlation between the relative proportion of ka-

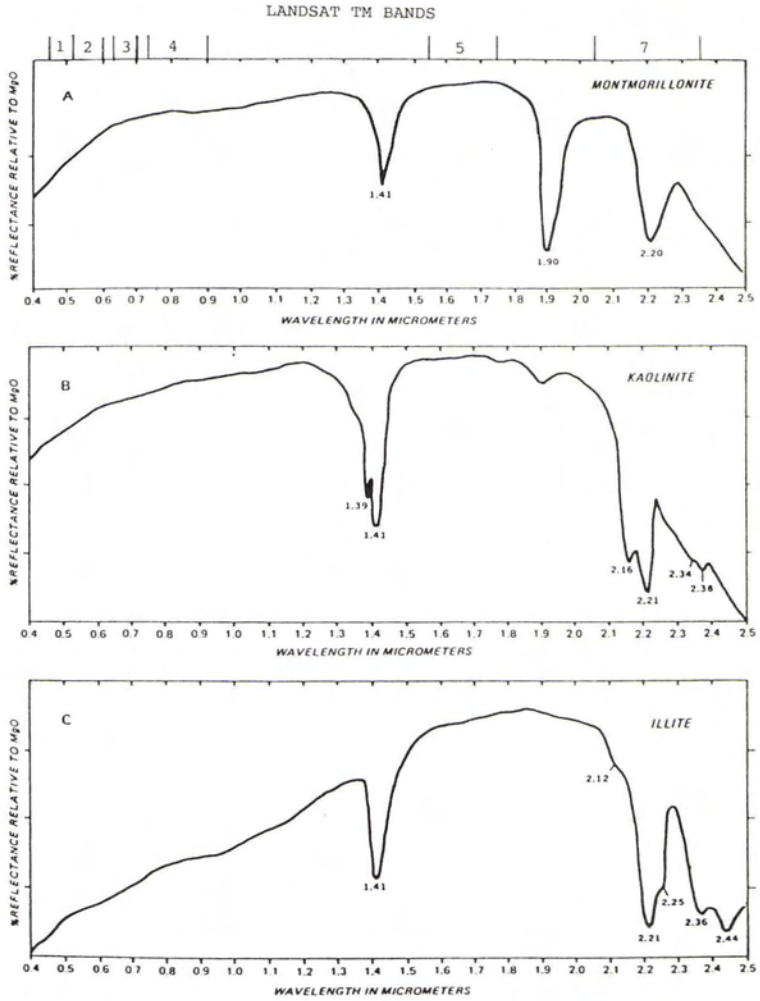

FIG. 3. Laboratory spectral reflectance curves for montmorillonite, kaolinite, and illite, showing the location of the Landsat TM spectral bands.

olinite and hydrocarbon production at the Lisbon Field. High-resolution airborne and laboratory spectral reflectance data suggests that both suites of bleached rocks exhibit more prominent 2.2-micrometre absorption features than do the unbleached rocks (Segal *et al.*, 1986). Additionally, bleached rocks associated with the production at the Lisbon Field were found to have even more prominent 2.2-micrometre absorption features than the bleached rocks located further south in the Three Step Hill area that are not associated with hydrocarbon production.

The relative increase in 2.2-micrometre band depth observed in the Wingate overlying the production at the Lisbon Field could be caused by an overall increase in clay mineral content. Alternatively, if a given clay mineral exhibits very strong or very deep 2.2-micrometre absorption characteristics, this effect could be caused by a relative increase in the proportion of that particular clay mineral. Clay mineral absorption band depth in the 2.2-micrometre wavelength region can also vary as a function of grain-size (Hunt and Salisbury, 1970), such that larger grain-sizes produce stronger absorption features relative to the same amount of smaller-sized grains.

Whole-rock x-ray diffraction studies, in conjunction with petrographic analyses, have shown that there is virtually no difference in total percent clay between the unbleached rocks and both suites of bleached Wingate examined (Merin and Segal, in press). However, detailed clay-sized fraction x-ray diffraction analyses do show significant differences in the relative proportion of kaolinite between the unbleached and two areas of bleached Wingate (Figure 4). Unbleached Wingate was found to contain large amounts of illite and mixed-layer clays, and minimal amounts of kaolinite. Bleached rocks in the Three Step Hill area contained relatively equal amounts of kaolinite and other clay minerals. Bleached rocks associated with the hydrocarbon production at the Lisbon Field contained large amounts of kaolinite, primarily as large-sized grains of pore-filling material, and minor amounts of illite and mixed-layer clays (Merin and Segal, in press). The petrographic data, and subsequent determination of the paragenetic sequence, suggest that the kaolinite is post-depositional and was derived from the alteration of detrital potassium feldspar grains and the dissolution of mixed-layer clays. Eh/pH considerations require that the fluids that bleached the Wingate Formation must have been acidic, as well as reducing, lending further credence to the microseepage hypothesis.

These differences in the relative proportion of kaolinite present have profound implications for hydrocarbon exploration using remotely sensed data. Kaolinite exhibits a very strong absorption feature centered at 2.2 micrometres, as well as the presence of a diagnostic, subordinate, absorption feature (known as a

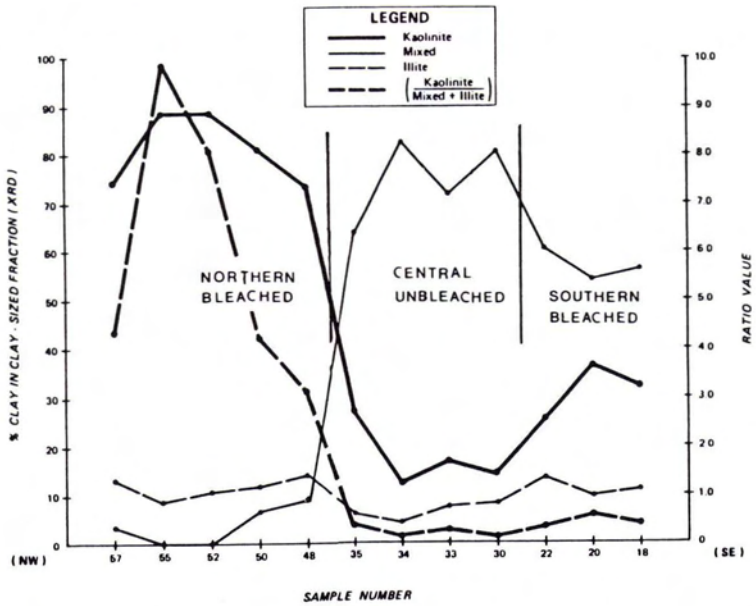

FIG. 4. Geographic distribution of kaolinite, mixer-layer clay, and illite in the northern bleached, unbleached, and southern bleached portions of the Wingate Formation at Lisbon Valley.

doublet) centered at 2.16 micrometres (Figure 3). Relative to most of the other clay minerals that are indigenous to sedimentary rocks, kaolinite tends to have the lowest reflectance in the broadly defined Landsat TM band 7 wavelength region relative to TM band 5. This is evidenced by examination of Figure 5, which shows typical laboratory spectra to the northern bleached, unbleached, and southern bleached portions of the Wingate Formation. Additionally, because the kaolinite associated with bleached rocks overlying the Lisbon Field occur as large, pore-filling grains, further deepening of the 2.2-micrometre region absorption band might also be expected. Thus, although the breadth of the near-infrared Landsat TM bands does not provide enough spectral resolution to enable unique discrimination of the diagnostic clay mineral absorption features, the results of

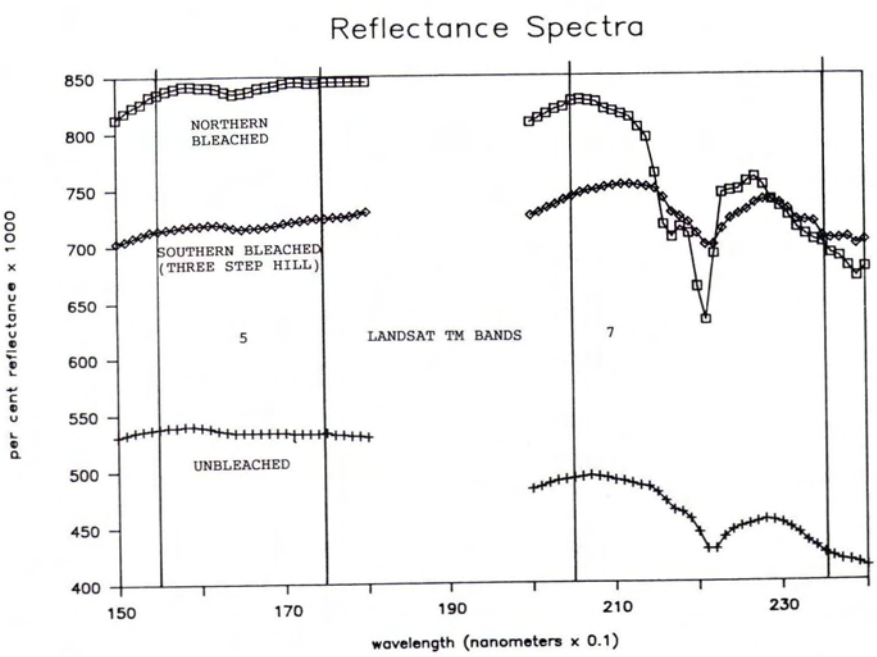

FIG. 5. Laboratory spectra for the northern bleached, unbleached, and southern bleached portions of the Wingate Formation. Note the differences in reflectance between the 1.6- and 2.2-micrometre wavelength regions.

previous studies suggest that it should be possible to utilize differences in the broad 2.2-micrometre TM band 7 region as a guide to the presence of microseepage-induced kaolinite in this area. The ability to discriminate these clay mineral variations with Landsat TM data may provide a basis for delineating microseepage-related mineralogic alteration in other areas of exploration interest.

METHODS

In order to determine if the spectral and mineralogical trends observed in the previous studies could be resolved with Landsat TM data, a series of conceptually straightforward digital enhancement techniques were applied to a portion of a TM scene covering the Lisbon Valley study area. Landsat TM scene 50262-17260 (path 36, row 33) was selected for the analysis.

A natural color composite, consisting of TM bands 1, 2, and 3 (displayed as blue, green, and red, respectively), was generated in order to define the location of bleached and unbleached exposures of the Wingate Formation on the basis of surface brightness differences.

A series of band-ratios were used to define

- The distribution of ferric-iron rich and ferric-iron poor rocks,
- The presence and distribution of clay minerals, and
- The location and extent of vegetation cover.

Figure 6 contains some generalized spectral reflectance curves for vegetation (A), limonitic (ferric-iron bearing) clay-poor rock (B), nonlimonitic moderately clay-rich rock (C), and nonlimonitic clay-rich rock (D). The limonitic clay-poor rock spectrum (B) is characteristic of the unbleached Wingate exposed at Lisbon Valley. The nonlimonitic moderately clay-rich spectrum (C) is characteristic of the bleached exposures located in the Three Step Hill area. The nonlimonitic clay-rich rock spectrum is characteristic of the bleached Wingate that overlies the hydrocarbon accumulation at the Lisbon Field.

Selection and Processing of Band Ratios

A ratio of TM bands 2 and 3 (2/3) was used to delineate variations in ferric-iron content. Because ferric-iron rich rocks exhibit a sharp fall-off in reflectance from approximately 0.8 micrometres to shorter wavelengths (Hunt *et al.*, 1971; Hunt, 1977), ferric-iron rich exposures exhibit very low 2/3 ratio values (Figure 6). Alternatively, ferric-iron poor rocks have relatively high 2/3 ratio values. Vegetation, due its higher reflectance in TM band 2 (visible green) relative to TM band 3 (visible red), also yields high 2/3 ratio values.

A ratio of TM bands 5 and 7 (5/7) was used to define the location and relative proportion of clay minerals. As previously noted, clay minerals exhibit absorption bands in the 2.2-micrometre region (TM band 7) and have high reflectance in the 1.6-micrometre wavelength (TM band 5) region (Figure 6). In general, clay-poor rocks are expected to exhibit relatively low 5/7 ratio values, whereas clay-rich rocks should yield high 5/7 ratios. However, because the total percent clay within both the bleached and unbleached Wingate is constant, and the mineralogic differences observed are a function of the relative proportion of kaolinite, it is expected that the 5/7 ratio will vary in relation to the percent kaolinite present.

Notably, vegetation, due to the abundance of molecular water, has lower reflectance in TM band 7 relative to TM band 5 (Figure 6). Thus, vegetated areas will also exhibit high 5/7 ratio values.

Therefore, "clay-rich" rocks and vegetation yield ambiguous results in the 5/7 ratio and additional information is required in order to differentiate them from each other.

A ratio of TM bands 3 and 4 (3/4) was used in order to uniquely define the distribution of vegetation (Figure 6). Because vegetation has very low reflectance in TM band 3 (visible red) relative to TM band 4 (short-wave infrared), vegetation is expected to exhibit very low 3/4 ratio values. Both ferric-iron rich and ferric-iron poor rocks will have considerably higher 3/4 ratio values.

Schematic histograms showing the relative location of limonitic and nonlimonitic rocks, clay-rich and clay-poor rocks, and vegetation within the 2/3, 5/7, and 3/4 ratio distributions are shown in Figure 7.

Because the human eye is much more sensitive to color variations than gray-tones, a standard five-level color coding

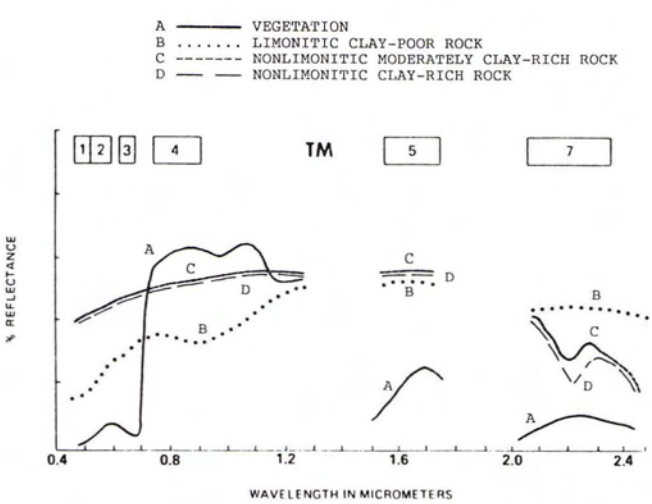

FIG. 6. Generalized reflectance curves for vegetation (A), limonitic (ferric-iron bearing) clay-poor rock (B), nonlimonitic moderately clay-rich rock (C), and nonlimonitic clay-rich rock (D).

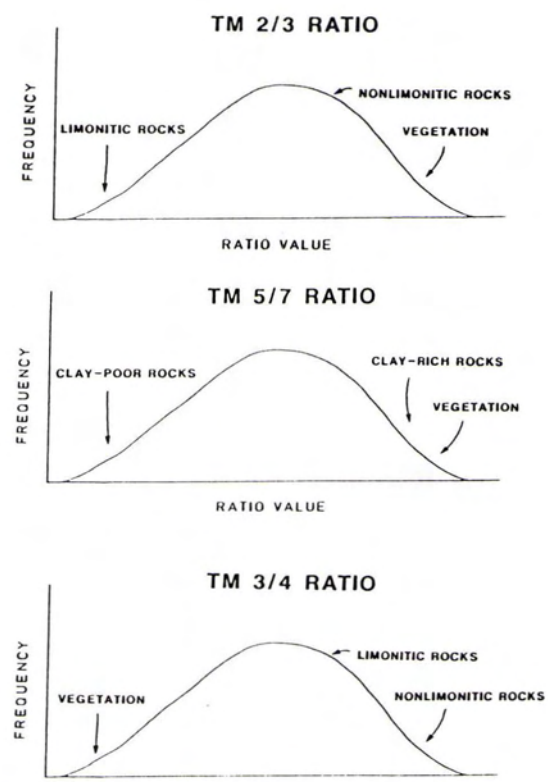

FIG. 7. Schematic histograms showing the relative location of limonitic and nonlimonitic rocks, clay-rich and clay-poor rocks, and vegetation in the 2/3, 5/7, and 3/4 TM band ratio distributions.

PLATE 1. Landsat TM natural color composite image. TM bands 1, 2, and 3 are displayed as blue, green, and red, respectively.

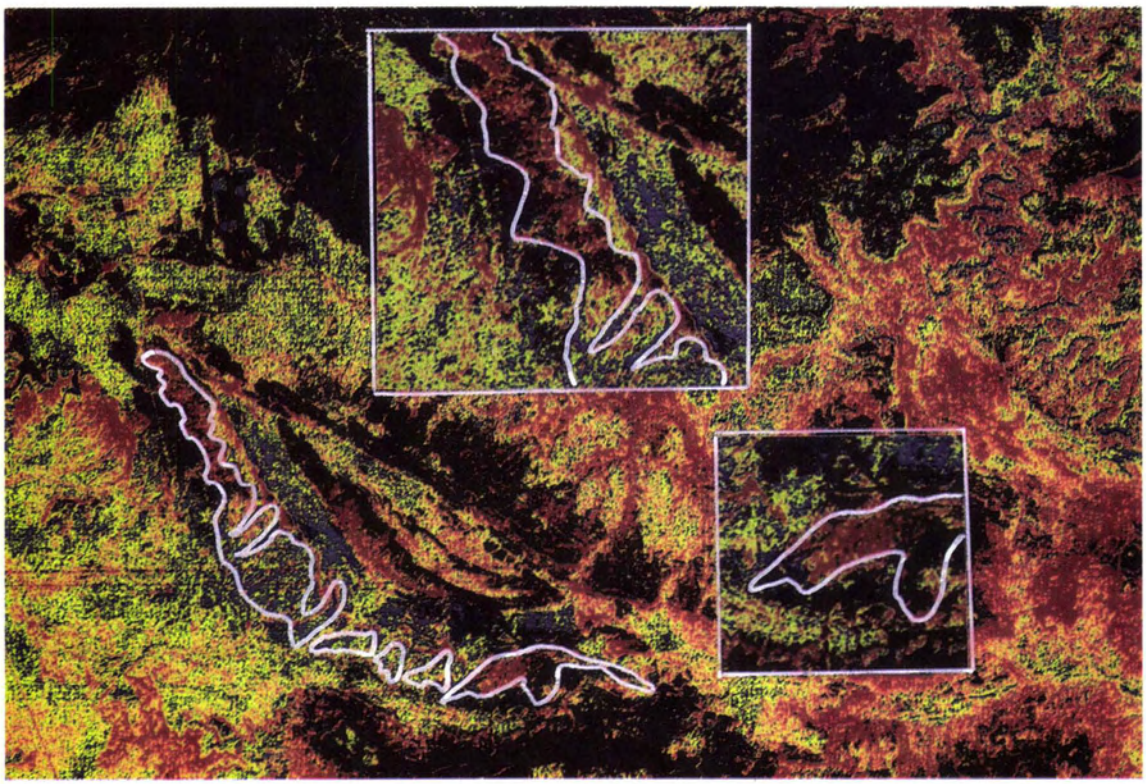

PLATE 2. Color coded Landsat TM 2/3 ratio image. Ferric-iron rich (limonitic) rocks are shown in blue, moderately limonitic rocks are green, and nonlimonitic rocks are red. Note the similar ratio signatures in both the northern and southern bleached areas.

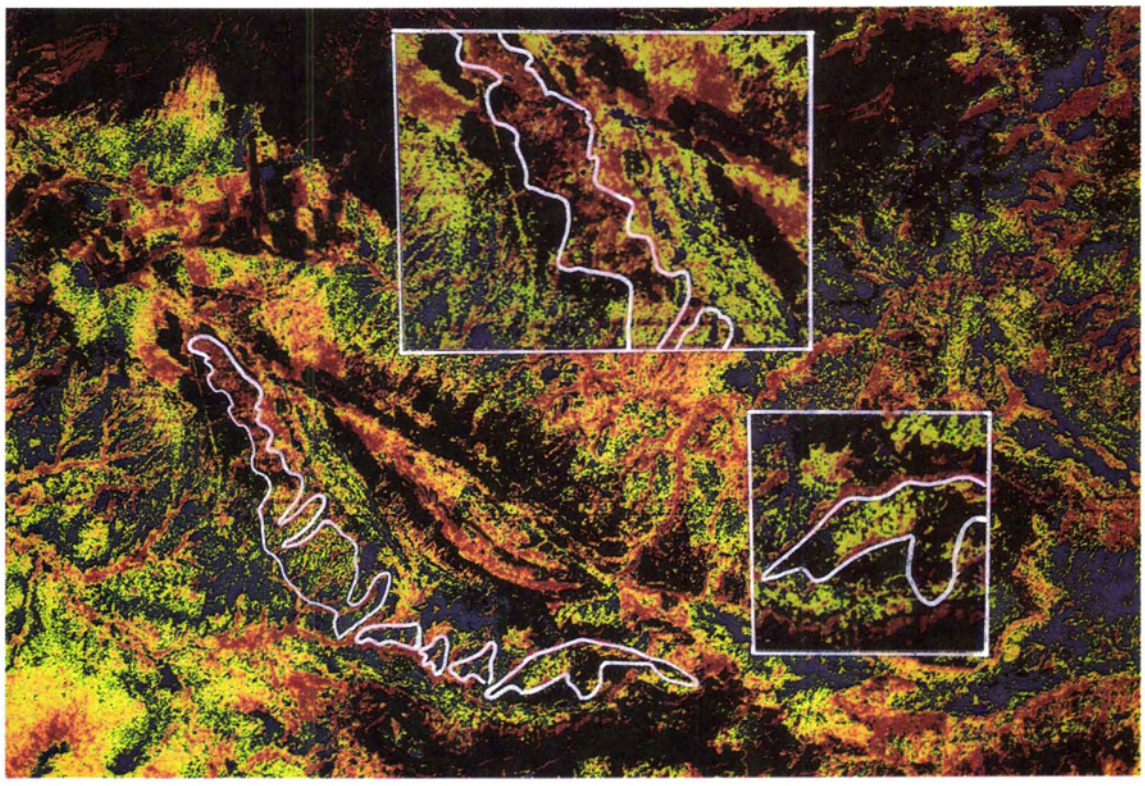

PLATE 3. Color coded Landsat TM 5/7 ratio image. Unbleached, relatively kaolinite-poor rocks are shown in blue, green, or yellow. Bleached exposures in the Three Step Hill area are moderately kaolinite rich and appear yellow. Bleached rocks that overlie the Lisbon Field are relatively kaolinite-rich and appear red.

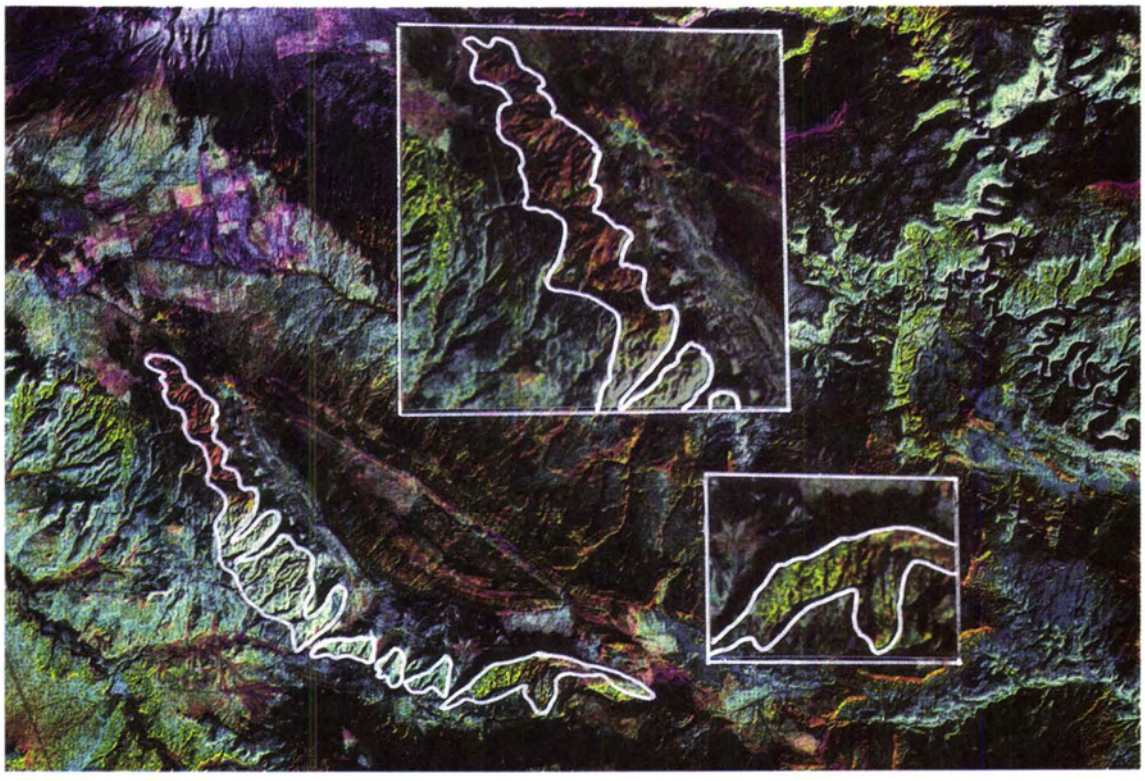

PLATE 4. Landsat TM IHS image. TM band 5 was used to dictate image intensity, whereas the 5/7 and 2/3 ratios were used to control the image hue and saturation, respectively. Note dramatic separation between the bleached exposures in the Three Step Hill area and the bleached rocks that overlie the Lisbon Field.

scheme (density slice) was applied to the 2/3 and 5/7 ratio images. The ratio-value color scheme used was as follows:

Ratio Value		Color
Lowest	-->	Blue
		Green
Moderate	-->	Yellow
		Orange
Highest	-->	Red

In order to alleviate potential ambiguities between vegetation, clay-rich rocks and nonlimonitic rocks, a binary image of the 3/4 ratio was generated and used as a mask on the 2/3 and 5/7 ratio density sliced images (Segal and Podwysocki, 1980; Podwysocki *et al.*, 1983). A threshold value of 0.85 was used as a cutoff for defining vegetated areas within the 3/4 ratio. This threshold was determined through a process of iterative comparison with a standard false-color composite image (TM 2 (blue), 3 (green), and 4 (red)) as well as examination of color infrared photography and field mapping. Pixels that had ratio values that were less than or equal to 0.85 in the 3/4 ratio were shown in black. Those pixels that had 3/4 ratio values in excess of 0.85 were not masked out and therefore display a color related to the value in the underlying density sliced ratio image.

The construction of a mask that defines vegetation is critical for the proper interpretation of the 5/7 ratio image because, as previously noted, both clay-rich rocks and vegetation yield very high values. The masking of vegetation is also important for the interpretation of the 2/3 ratio image because both vegetation and ferric-iron poor rocks have relatively high values (Figure 7).

Construction of the IHS Image

Image information derived from disparate types of data can be merged and displayed using a computer processing technique known as the Intensity, Hue, and Saturation (IHS) transformation. The IHS concept relies on the fact that any color can be described on the basis of its intensity (brightness), hue (color), and saturation (purity of color). Various image components can be used to control either intensity, hue, or saturation, and the characteristics of the resulting product will depend on the nature of the components used and the order of their assignments. The IHS transformation technique is especially useful for merging band ratio images with other image data because ratios tend to be noisy and typically lack the topographic or spatial detail required to properly locate observed features.

An IHS image was constructed for the Lisbon Valley study area in order to show the correspondence between bleached areas and clay mineral content in a single image product. The following band/IHS assignments were used:

TM Band	Component
5	Intensity
5/7	Hue
2/3	Saturation

The TM band 5 (1.6-micrometre) image was selected to control the output image intensity because most rocks are bright in this wavelength region and data quality is typically high. The 5/7 ratio image was used to dictate hue, which can be viewed in an analogous way as the density slice color coding scheme noted above. Thus, areas that exhibit low 5/7 ratios (clay-poor rocks) will appear blue, and high 5/7 ratios (clay-rich rocks) will appear red. The 2/3 ratio image was used to control the output image saturation, such that areas that exhibit low 2/3 ratio values (ferric-iron rich rocks) will yield unsaturated colors and high 2/3 ratio values (ferric-iron poor rocks) will result in saturated colors. By assigning the 5/7 ratio to hue and 2/3 ratio to saturation, colors, as defined by the 5/7 ratio, will appear saturated only if they are associated with ferric-iron poor (or bleached) rocks. Thus, it is possible to uniquely define and map variations in clay content specifically in those areas that are bleached.

RESULTS

Natural Color Composite Image

Examination of the TM natural color composite image (Plate 1) shows that bleached and unbleached exposures of the Wingate Formation are readily separable on the basis of differences in surface brightness. Unbleached exposures are substantially darker than bleached exposures and appear reddish, due to the abundance of ferric-iron bearing minerals. No differences in the degree of bleaching are apparent between the bleached exposures in the Three Step Hill area and those that overlie the production at the Lisbon Field.

TM 2/3 Density Slice

Evaluation of the 2/3 ratio density slice image (Plate 2) reveals that the distribution of bleached and unbleached exposures is mappable on the basis of differences in ferric-iron content. Unbleached exposures have the lowest 2/3 ratio values and appear blue in the density slice image. Bleached exposures have very high 2/3 ratio values and generally appear red or orange in the density slice image. Vegetation also exhibits high 2/3 ratio values; however, heavily vegetated areas have been masked out using the 3/4 ratio and are shown in black. Note that both bleached areas appear the same in this image, suggesting that there is no difference in the degree of ferric-iron loss.

TM 5/7 Density Slice

Examination of the TM 5/7 ratio density slice image (Plate 3) shows that bleached and unbleached exposures of the Wingate Formation are separable on the basis of differences in 5/7 ratio values and that further distinction between the two bleached areas is also readily apparent. Unbleached exposures, which are known to have a small proportion of kaolinite, have relatively low 5/7 ratio values. These exposures appear blue, green, or yellow in the color coded image. Bleached exposures in the Three Step Hill area, which contain a moderate proportion of kaolinite, have relatively higher 5/7 ratio values and appear yellow in the density slice image. Bleached exposures that overlie the Lisbon Field have the largest relative proportion of kaolinite, and appear red in the density slice image.

As previously noted, vegetation also yields high 5/7 ratio values and can be confused with clay-rich rock exposures. However, this potential ambiguity has been alleviated by using the 3/4 ratio as a mask to eliminate vegetated areas, which are shown in black. Thus, it is clear that the differences observed between the two bleached areas are due to mineralogic variations, and not due to differences in vegetation type or concentration.

TM IHS Image

Examination of the IHS transformation image (Plate 4) reveals mineralogic differences that are a function of both ferric-iron and clay mineral content apparent in the 2/3 and 5/7 ratio images, yet retains the important spatial information derived from TM band 5. In this image, note that the ferric-iron poor (bleached) kaolinite-rich exposures of the Wingate Formation that overlie the Lisbon Field appear saturated red, due to the high 2/3 and 5/7 ratio values. The ferric-iron poor, moderately kaolinite-rich exposures in the Three Step Hill area exhibit saturated green and yellow colors due to the relatively lower 5/7 ratio values. Unbleached exposures of the Wingate exhibit unsaturated colors, due to the low 2/3 ratio values indicative of the presence of ferric-iron rich minerals.

CONCLUSIONS

Previous research suggested that hydrocarbon microseepage-induced mineralogic differences observed between the two bleached and unbleached exposures of the Wingate Formation at Libson Valley should be discernible with Landsat TM data. A series of image enhancement techniques were applied to a portion of a Landsat TM scene covering the Lisbon Valley study area in order to evaluate its effectiveness for discriminating subtle microseepage-induced variations in clay and ferric-iron bearing mineral content.

The results of the analysis show that the bleached and unbleached exposures of the Wingate can be distinguished using TM data on the basis of differences in ferric-iron content of the respective exposure. This discrimination was accomplished by use of a TM 2/3 ratio, which was color coded in order to highlight differences between ferric-iron rich and ferric-iron poor exposures. A 3/4 ratio was used to define vegetation and used as a mask on the 2/3 ratio image in order to alleviate confusion between ferric-iron poor rocks and vegetation.

Variations in clay mineral content, which have been directly correlated with differences in the relative proportion of kaolinite, were defined using a color coded TM 5/7 ratio. Kaolinite-poor rocks associated with unbleached exposures were found to have relatively low 5/7 ratio values. Moderately kaolinite-rich rocks associated with bleaching in the Three Step Hill area had higher 5/7 ratio values. Kaolinite-rich rocks associated with bleached exposures that overlie the hydrocarbon accumulation at the Lisbon Field exhibited the highest 5/7 ratio values. A 3/4 ratio was used to define vegetation and was used as a mask in order to alleviate confusion between vegetation and clay enrichment.

An IHS image, constructed using information from both the 2/3 and 5/7 ratio images, was generated in order to depict variations in ferric-iron and clay mineral content. Differences in the degree of kaolinite enrichment between the two bleached exposures were readily apparent.

These results verify that TM data can be used to map subtle spectral variations that have a direct correspondence with hydrocarbon microseepage-induced phenomena. Because of its widespread availability and sensitivity to subtle variations in iron and clay mineral content, the extrapolation of these results has profound implications for the use of TM data for mapping subtle mineralogic variations in other areas of exploration interest.

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