



Remote detection and geochemical studies for finding hydrocarbon-induced alterations in Lisbon Valley, Utah

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ABSTRACT

Long-term hydrocarbon microseepages develop diverse arrays of chemical and mineralogical changes in rocks and soils. Alterations that are reported to have affected the Wingate Sandstone, Lisbon Valley, Utah, include bleaching of red beds, precipitation of high limonite and carbonate concentrations, anomalous weathering patterns, and high clay content.

To investigate sandstone color alteration patterns, spectroscopy, ASTER multispectral remote sensing and Synthetic Aperture Radar (SAR) data were used as well as geochemical analyses of selected samples. Using ASTER satellite images and SAR data, the altered areas of the Wingate Sandstone were identified and mapped at the northwest and southwest part of the Lisbon Valley anticline. Based on sandstone color alteration patterns three different zones were identified in the Wingate Sandstone; the southwest zone is the most altered, the middle part is unaltered, and the northwest part shows minor alteration. Spectroscopy and thin section studies revealed higher content of clay minerals in altered than in unaltered zones. Major elemental concentrations suggest removal of iron cement and addition of calcite during diagenesis. Trace elemental concentrations in selected altered sandstone samples are characteristic of geochemical halos forming over oil fields.

The methodology being developed in this work can provide a completely new technique for petroleum exploration in remote regions of the world where field work is difficult.

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1. Introduction

The objective of this study is to map and investigate the role of hydrocarbon microseepages in rock alteration. The Wingate Sandstone in Lisbon Valley, Utah, provides an ideal case study. Hydrocarbon microseepages are light hydrocarbons that move to the surface through their seal rocks (Horvitz, 1980). Direct evidence of hydrocarbon microseepages includes the presence of significant amounts of non-biogenic hydrocarbons, such as ethane or butane, in soils (Horvitz, 1980). Indirect evidence includes a suite of closely interrelated geomorphic, chemical, geobotanical, mineralogical, and geophysical anomalies. Leaking hydrocarbons and associated fluids, such as hydrogen sulfide, produce a reducing environment, thereby initiating diagenetic Eh/pH controlled reactions in the rocks and soils overlying hydrocarbon accumulations. These chemical reactions cause dissolution and mobilization of various compounds as well as precipitation of minerals in the stratigraphic column above the leaking reservoir. Mineralogical changes can, in turn, promote geomorphic and physical alteration of the surface and near-surface

strata and may be detected using remote sensing techniques (Segal et al., 1986) and ground based geochemical tools. These changes can include: bleaching of red beds, radioactive anomalies, clay mineralization, visual tonal and textural anomalies, carbonate cementation, magnetic anomalies, vegetation anomalies, electrochemical changes, occurrence of sulfides, uranium, and so on.

There are many locations in the United States where rock and soil alteration caused by hydrocarbon microseepages have been reported (Fig. 1). They typically occur in the western United States, above documented oil and gas fields. A detailed list of all the locations and associated alterations is presented in Table 1.

Lisbon Valley is located in the southeast part of Utah, in San Juan County (Fig. 2). It is a northwest-trending, doubly-plunging anticline. The core of the fold (mainly salt) has been breached by erosion and undergone subsequent collapse (Segal et al., 1986). The alteration related to hydrocarbon microseepages in Lisbon Valley includes the bleaching of red beds, high clay concentrations, carbonate cementation of sandstones, uranium mineralization, and the presence of sulfides.

The stratigraphic sequence exposed in Lisbon Valley includes units from the Pennsylvanian Hermosa Group through the Cretaceous Burro Canyon Formation (Fig. 3). The pre-Hermosa strata of Cambrian, Devonian, and Mississippian age underlie the exposed sequence. The rocks that produce hydrocarbons at this location are

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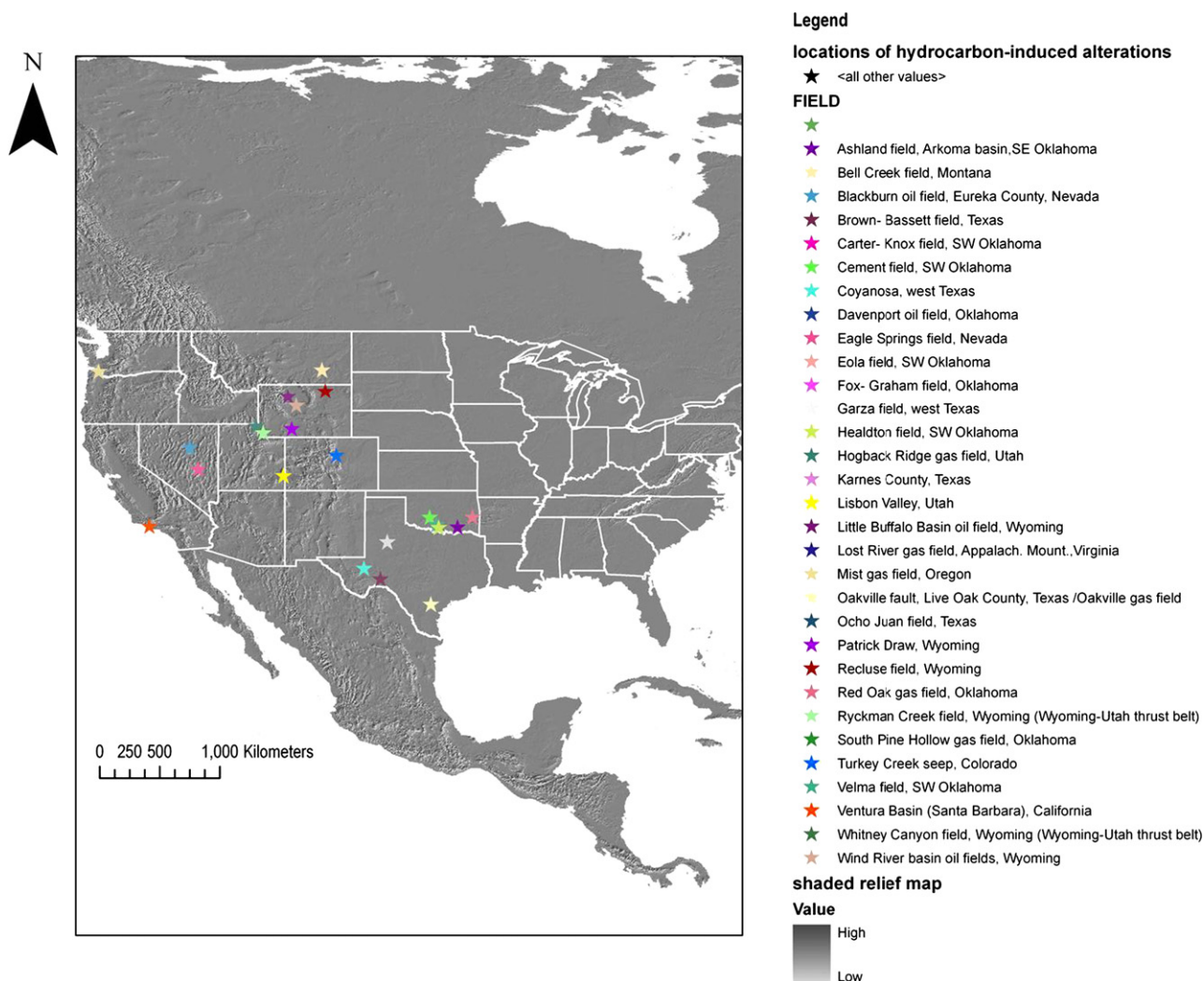


Fig. 1. Shaded relief map of the continental USA showing locations of hydrocarbon-related alterations reported in the literature represented by stars (data from Love, 1957; Eargle and Weeks, 1973; Donovan, 1974; Olmstead, 1975; Goldhaber et al., 1978; Donovan et al., 1979; Ferguson, 1979a,b; Dalziel and Donovan, 1980; Donovan et al., 1981; Abrams et al., 1984; Allen and Thomas, 1984; Duchscherer, 1984; Lilburn and Al-Shaieb, 1984; Oehler and Sternberg, 1984; Segal et al., 1984, 1986; Reynolds et al., 1984, 1988, 1990; Conel and Alley, 1985; Lang and Nadeau, 1985; Roeming and Donovan, 1985; Richers et al., 1986; McCoy and Wullstein, 1988; McCoy et al., 1989; Scott, 1989; Arp, 1992; Klusman et al., 1992; Reid et al., 1992; Al-Shaieb et al., 1994; Bammel et al., 1994; Campbell, 1994; Schumacher, 1996; Jengo and Vincent, 1999; Van der Meer et al., 2002; Jacobson, 2006; Petrovic, 2006).

of Devonian, Mississippian, Pennsylvanian, and Permian age (Segal et al., 1986).

The Wingate Sandstone is the focus of this study, and accumulated as a Lower Jurassic eolian depositional system, composed primarily of dune and sandsheet deposits that are part of an erg margin. The Wingate is easily recognized as orange-red, thick-bedded, erosion resistant, and cliff-forming sandstone that is prominently displayed in the southwest dipping cuesta of the west flank of the Lisbon Valley anticline (Fig. 3). Steep to vertical cliffs display pervasive vertical joints, planar cross-bedding on a large scale, and show the effects of spalling of huge blocks of sandstone along vertical joint faces (Segal et al., 1986). The Wingate Sandstone is considered to be a part of the Glen Canyon Group, together with the Kayenta and Navajo formations. It is the lowermost part of the group. The Wingate Sandstone in Lisbon Valley area is generally about 90 m thick (Weir and Puffett, 1981), but because of its cliff-forming habit it is mostly inaccessible and difficult to precisely measure.

The Wingate Sandstone is bleached on the southwest flank of the Lisbon Valley anticline. In these areas the bleached rocks are gray and also display somewhat different mineralogical and weathering patterns than the unaltered strata from the northern flank of an anticline. The bleached rocks contain higher abundances

of limonite and carbonate as well as kaolinite and other clay minerals. The Wingate Sandstone has changed from an erosionally resistant to a friable unit that easily weathers (Segal et al., 1984, 1986).

The Lisbon field produces oil and gas from the southwest flank of a faulted anticlinal trap in the Devonian sandstones and Mississippian limestones (Segal et al., 1986). Hydrocarbon accumulation in the Mississippian is controlled by a fault on the northeast side of the structure, which exhibits a throw of 366–488 m. Closure of the structure is estimated at 579 m, with an associated 549 m oil column (Clark, 1978). Thus, the hydrocarbon reservoir is filled almost to the spill point, making it an ideal location for study of the effects of vertical gas leakage (Segal et al., 1986). This study documents the presence of alteration of the Wingate Sandstone in the northwest part of the Lisbon Valley anticline.

2. Rock alterations in Lisbon valley, Utah

2.1. Bleaching of red beds

Chemical reduction due to interaction with hydrocarbons can result in removal of hematite and its transformation to pyrite,

Table 1

The table lists locations in the continental US of reported hydrocarbon-induced alterations

Field/area	Bleaching of red beds		Weathering	Clay minerals	Carbonate mineralizations and cements	Magnetic minerals	Sources
Lisbon Valley, Utah	X		X	X			Segal et al. (1984, 1986), Conel and Alley (1985), Lang and Nadeau (1985), Schumacher (1996), Petrovic (2006)
Patrick Draw, Wyoming				X	X		Abrams et al. (1984), Richers et al. (1986), Scott (1989), Arp (1992), Jacobson (2006)
Cement field, SW Oklahoma	X			X	X	X	Donovan (1974), Olmstead (1975), Goldhaber et al. (1978), Ferguson (1979a,b), Allen and Thomas (1984), Lilburn and Al-Shaieb (1984), Reynolds et al. (1984, 1988, 1990), Al-Shaieb et al. (1994)
Recluse field, Wyoming							Dalziel and Donovan (1980)
Velma field, SW Oklahoma	X				X		Ferguson (1979a,b), Donovan et al. (1981), Al-Shaieb et al. (1994)
Healdton field, SW Oklahoma	X				X		Al-Shaieb et al. (1994)
Eola field, SW Oklahoma	X						Ferguson (1979a,b), Al-Shaieb et al. (1994)
Carter-Knox field, SW Oklahoma	X				X		Al-Shaieb et al. (1994)
Ashland field, Arkoma basin, SE Oklahoma	X				X		Ferguson (1979a,b), Oehler and Sternberg (1984)
Turkey Creek seep, Colorado	X			X	X		Reid et al. (1992)
Mist gas field, Oregon	X				X		Campbell (1994)
Brown-Bassett field, Texas	X				X		Campbell (1994)
Little Buffalo Basin oil field, Wyoming					X		Bammel et al. (1994)
Coyanosa, west Texas					X		Lang and Nadeau (1985)
Hogback Ridge gas field, Utah							Campbell (1994)
Garza field, west Texas	X						Donovan et al. (1979)
Wind River basin oil fields, Wyoming	X						Love (1957), Jengo and Vincent (1999)
Oakville gas field, Texas							Eargle and Weeks (1973)
Bell Creek field, Montana							Dalziel and Donovan (1980), Duchscherer (1984), Roeming and Donovan (1985)
Blackburn oil field, Eureka County, Nevada							McCoy and Wullstein (1988), McCoy et al. (1989)
Eagle Springs field, Nevada							Klusman et al. (1992)
Ventura Basin (Santa Barbara), California					X		Van der Meer et al. (2002)
Field/area	Sulfides	Uranium	Biogeochemical anomalies	Electrochemical changes (induced polarization)	Trace elements	Vegetation anomalies	Sources
Lisbon Valley, Utah	X	X			X		Segal et al. (1984, 1986), Conel and Alley (1985), Lang and Nadeau (1985), Schumacher (1996), Petrovic (2006)
Patrick Draw, Wyoming						X	Abrams et al. (1984), Richers et al. (1986), Scott (1989), Arp (1992), Jacobson (2006)
Cement field, SW Oklahoma	X	X					Donovan (1974), Olmstead (1975), Goldhaber et al. (1978), Ferguson (1979a,b), Allen and Thomas (1984), Lilburn and Al-Shaieb (1984), Reynolds et al. (1984, 1988, 1990), Al-Shaieb et al. (1994)
Recluse field, Wyoming			X		X	X	Dalziel and Donovan (1980)
Velma field, SW Oklahoma	X						Ferguson (1979a,b), Donovan et al. (1981), Al-Shaieb et al. (1994)
Healdton field, SW Oklahoma	X						Al-Shaieb et al. (1994)
Eola field, SW Oklahoma	X						Ferguson (1979a,b), Al-Shaieb et al. (1994)
Carter-Knox field, SW Oklahoma	X						Al-Shaieb et al. (1994)
Ashland field, Arkoma basin, SE Oklahoma	X			X			Ferguson (1979a,b), Oehler and Sternberg (1984)
Turkey Creek seep, Colorado	X	X		X			Reid et al. (1992)
Mist gas field, Oregon	X			X			Campbell (1994)
Brown- Bassett field, Texas	X			X			Campbell (1994)
Little Buffalo Basin oil field, Wyoming							Bammel et al. (1994)
Coyanosa, west Texas							Lang and Nadeau (1985)
Hogback Ridge gas field, Utah	X						Campbell (1994)
Garza field, west Texas							Donovan et al. (1979)
Wind River basin oil fields, Wyoming							Love (1957), Jengo and Vincent (1999)
Oakville gas field, Texas		X					Eargle and Weeks (1973)
Bell Creek field, Montana					X	X	Dalziel and Donovan (1980), Duchscherer (1984), Roeming and Donovan (1985)
Blackburn oil field, Eureka County, Nevada					X	X	McCoy and Wullstein (1988), McCoy et al. (1989)
Eagle Springs field, Nevada					X	X	Klusman et al. (1992)
Ventura Basin (Santa Barbara), California							Van der Meer et al. (2002)

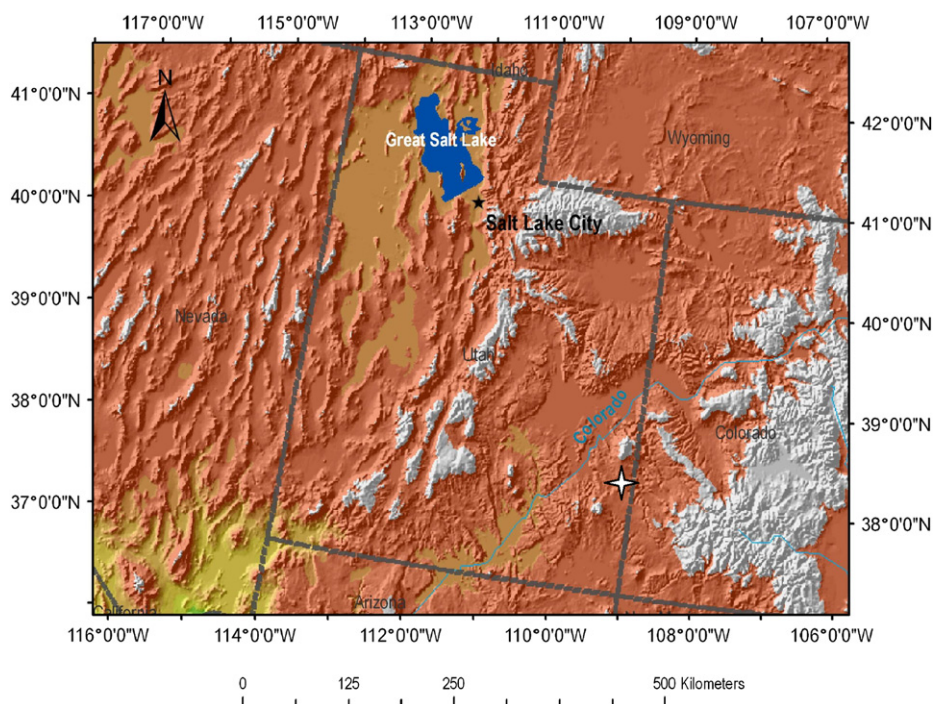


Fig. 2. Shaded relief map with the location of Lisbon Valley, Utah, represented with a white star.

magnetite, or siderite, with consequent bleaching of the red color (Schumacher, 1996). This has occurred in the Wingate Sandstone. The red color of the unbleached Wingate Sandstone results from a pervasive hematite–clay mixture coating virtually all sand grains, whereas the bleached Wingate facies lack disseminated hematite as grain-surface coatings (Schumacher, 1996). Segal et al. (1986) reported that the distribution of the bleached outcrops of the Wingate Sandstone approximates the geographic limits of the oil and gas reservoirs at depth. Additionally, unbleached portions of the Wingate Sandstone lack siderite, whereas the bleached portions contain siderite (Segal et al., 1986). Bleaching of red beds occurs when there are acidic or reducing fluids present that remove ferric oxide (hematite) and favor the formation of pyrite or siderite (ferrous ion) using the from the dissolution of hematite (Schumacher, 1996).

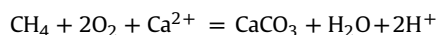
2.2. Anomalous clay concentrations

The production of different gases resulting from the microbial oxidation of hydrocarbons in near-surface soils and sediments can create reducing, slightly acidic environments that favor the alteration of feldspars to clays (Schumacher, 1996). Previous investigations in the Lisbon Valley area by Segal et al. in 1984 and 1986 provided the information that bleached Wingate Sandstone contains abundant kaolinite and minor amounts of feldspars. Unbleached exposures contain substantially less clay and more abundant feldspar. Overall, the bleached Wingate Sandstone contains significantly more clay (three to five times more) than the unbleached Wingate Sandstone.

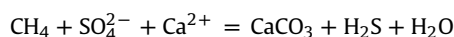
2.3. Carbonate mineralization

Replacement carbonates and carbonate cements in near-surface environments commonly occur as a byproduct of petroleum oxidation, particularly of methane, under both aerobic and anaerobic conditions, as has been described by Schumacher (1996):

1. Aerobic conditions:



2. Anaerobic:



Basically, carbon dioxide produced by anaerobic bacterial degradation or by oxidation of hydrocarbons forms carbonic acid, H_2CO_3 , in the groundwater. The carbonic acid can react with calcium silicates and result in diagenetic carbonate mineralization (Saunders et al., 1999). Carbonate (calcite) cement and anomalous carbonate concentrations are present in the Wingate Sandstone.

2.4. Anomalous weathering patterns

Bleached portions of Wingate sandstones are more easily eroded than unbleached areas. Hydrocarbon microseepages transform the Wingate Sandstone into a friable unit that weathers easily into bleached mounds (Segal et al., 1986).

3. Methodology

The Wingate Sandstone alteration, in the form of bleached beds, is extensive enough to be identified using remote sensing techniques. Also, all rock and soil changes carry certain geochemical hydrocarbon signatures, thus they can be analyzed with a number of ground-based geochemical tools.

3.1. Remote sensing techniques

This study was based on processing of an ASTER multispectral image and its fusion with Synthetic Aperture Radar data. ASTER

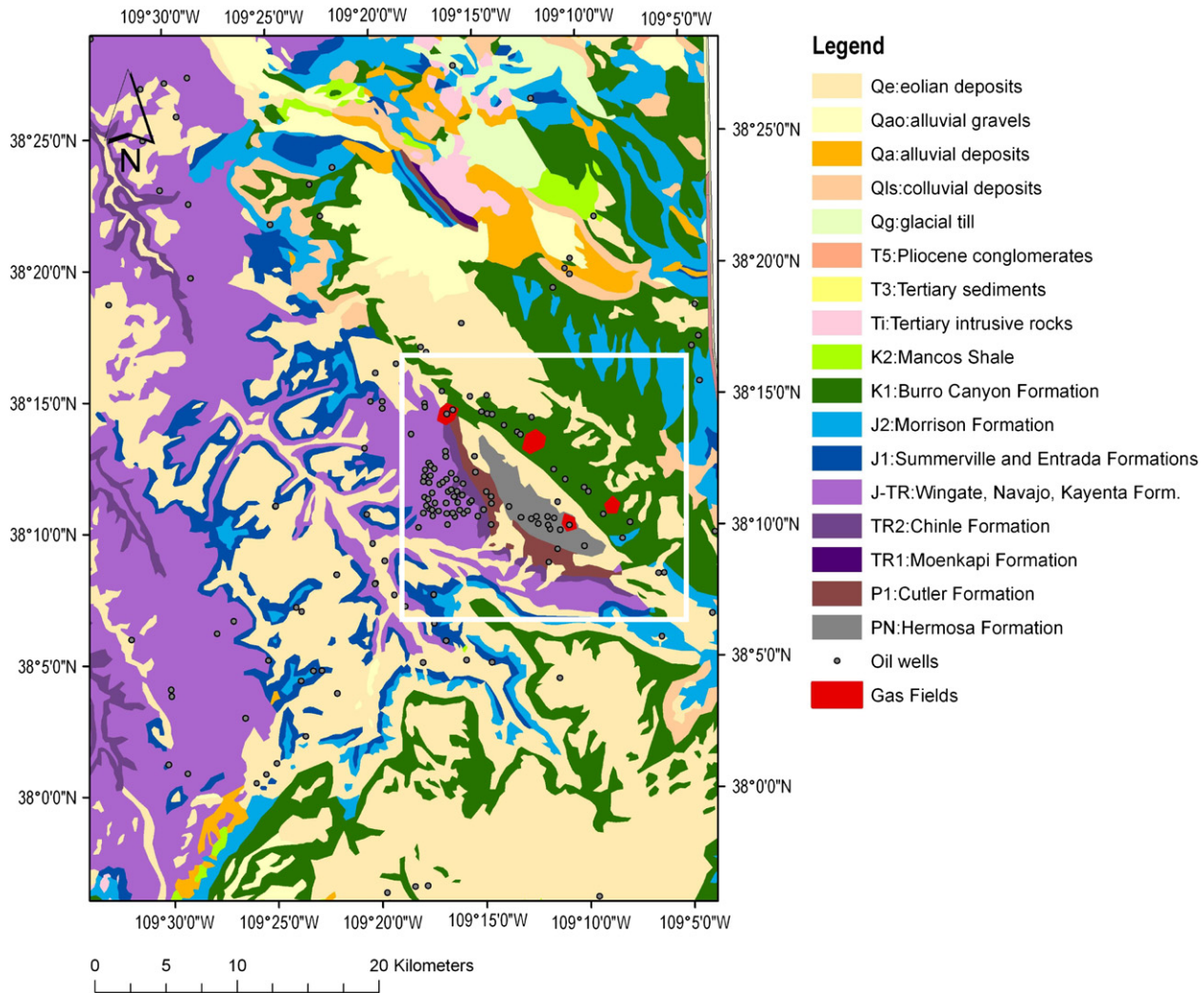


Fig. 3. Geologic map of Lisbon Valley and the surrounding area. Locations of oil and gas fields are also shown. White rectangle covers the area of Lisbon Valley. Sources: www.gis.usu.edu, www.dogm.nr.state.ut.us, and www.agrc.utah.gov.

image was obtained from USGS EROS data center (Fig. 4), whereas the JERS (Japanese Earth Resources Satellite) SAR data were acquired from Alaska Satellite Facility EDG (Earth Observing System Data Gateway). ASTER has 14 bands, covering the spectral range from visible to thermal infrared, with spatial resolution of 15, 30, and 90 m, and the spatial resolution for SAR data is 10 m. Remote sensing data were processed using ENVI 4.3 (the Environment for Visualizing Images) software, created by ITT Visual Information Solutions. Supervised Classification (maximum likelihood technique), Principal Component Analysis (PCA), and PC (Principal Component) Spectral Sharpening digital image classification techniques were used.

Digital image classification is a process of assigning pixels to classes. In a supervised classification, the identity and location of some of the land-cover types (e.g., urban, agriculture, wetland) are known *a priori* through a combination of fieldwork, interpretation of aerial photography, map analysis, and previous investigations (Okon and Cwick, 2005). The maximum likelihood technique, which is one of the available supervised classification techniques, calculates the conditional probabilities of membership in each class, and is based on standard deviation. A class assignment is made to the class to which the pixel is most likely to belong. The process was used to distinguish altered sandstones from the non-altered

surrounding areas, so the pixels for the classification were chosen from the bleached areas and the whole process was set to extract all the pixels with the same values throughout the ASTER scene. This technique was applied to the resized ASTER data for classification.

The Principal Component Analysis (PCA) is a useful statistical technique used to produce uncorrelated output bands, to segregate noise components, and to reduce dimensionality of datasets. Transformation of the raw remote sensor data using PCA can result in new principal component images that may be more readily interpretable than the original data. Principal Component bands produce more colorful composite images than spectral color composite images, because data are uncorrelated (Jensen, 2000). For the purpose of this study, the PCA analysis was performed on all parts of the spectrum.

The third remote sensing processing technique used is fusion of SAR data and ASTER image with a PC Spectral Sharpening method. PC Spectral Sharpening is used to sharpen spectral image data (in this case ASTER image) with high spatial resolution data (SAR image). In this way the principal component transformation is performed on multispectral data, which are then automatically resampled to the high resolution pixel size. Two PC Spectral Sharpening techniques were performed, one on the PCA result of

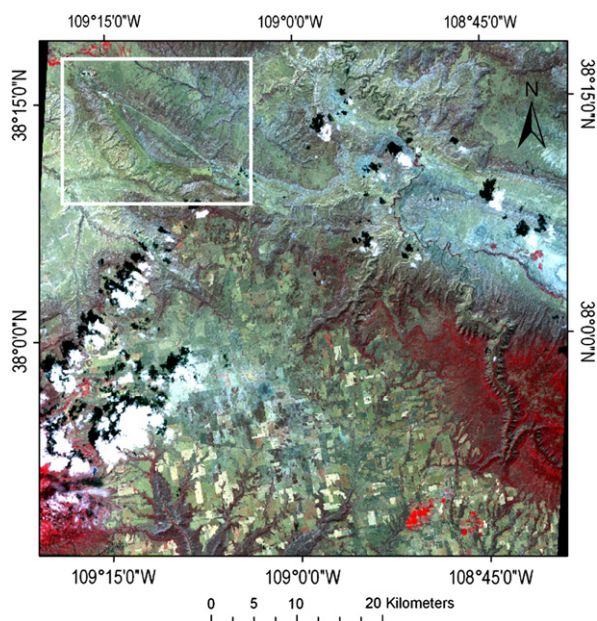


Fig. 4. ASTER image of Lisbon Valley and the surrounding area. Band combination used is (RGB) 3-2-1 (visible-near infrared part of the spectrum, 15 m resolution). Lisbon Valley is outlined with the white rectangle.

VNIR part of the ASTER image spectra and radar, and the other on VNIR bands of the ASTER image and radar data. The fusion of both datasets was used in order to see if some further differentiation of bleached areas was possible.

3.2. Geochemical tools

Two different geochemical analyses were used to analyze the bleached Wingate Sandstone rock samples: ICP-AES, to determine the major, minor, and trace elemental concentrations, and thin section analyses, to determine the abundance of clay minerals, carbonate cements, and hematite. Spectroscopy was then used to confirm the presence and/or absence of clays and iron minerals. ICP geochemical analyses as well as spectroscopy have been performed on altered, bleached rocks that have been first powdered in the laboratory. Thin sections were also prepared from the altered samples.

Elemental concentrations (for major, minor, and trace elements) were measured using a Thermo Jarred-Ash Atomic Scan 25 Inductively Coupled Plasma-Atomic Emission Spectrometer (ICP-AES) on the bleached samples of the Wingate Sandstone from Lisbon Valley.

The presence and the amount of clay minerals were observed in thin sections from altered, bleached rock samples using a 200-point counting method. This method was also used to record modal percentage of different minerals, and for observation of carbonate cementation and hematite abundance in samples of the bleached Wingate Sandstone.

The presence of clay minerals was confirmed by spectral measurements of rock samples (spectroscopy). Spectroscopy is the production, measurement, and analysis of electromagnetic spectra produced as a result of the emission or absorption of energy by various substances. In this case, the FieldSpec Pro (portable spectroradiometer) was used to measure reflectance values for all the rocks, which were then observed for diagnostic absorption and reflection features useful for selecting bands for further analyses. Spectral reflectance curves were measured for 12 altered Wingate Sandstone samples taken from the southwest part of the Lisbon Valley anticline.

4. Results

4.1. Remote sensing results

Remote sensing techniques identified altered sandstones along the southwest and northwest parts of the Lisbon Valley anticline. They also helped establish the relationship between altered and unaltered (middle part of the Wingate Sandstone exposure in Lisbon Valley) areas, and showed the difference in the degree of alteration between the northwest and southwest parts.

Alteration detected using a supervised classification-maximum likelihood technique is indicated in Fig. 5B in green. The most intense changes were mapped in the southwest part of Lisbon Valley, but significant bleaching also was detected at the northwest part of the Lisbon Valley anticline. Surficial exposure of the Wingate Sandstone between these two areas is considered unaltered because bleached rocks have not been recognized there during the processing of the remote sensing data, i.e., the orange colored areas between green areas. The processed image also shows the presence of bleached sandstones of the Wingate along the eastern part of the anticline, which have not been previously reported.

The second remote sensing processing technique, PCA, was performed on all parts of the spectrum, with the best results gained from the short-wave infrared (Fig. 6). This tool turned out to be very

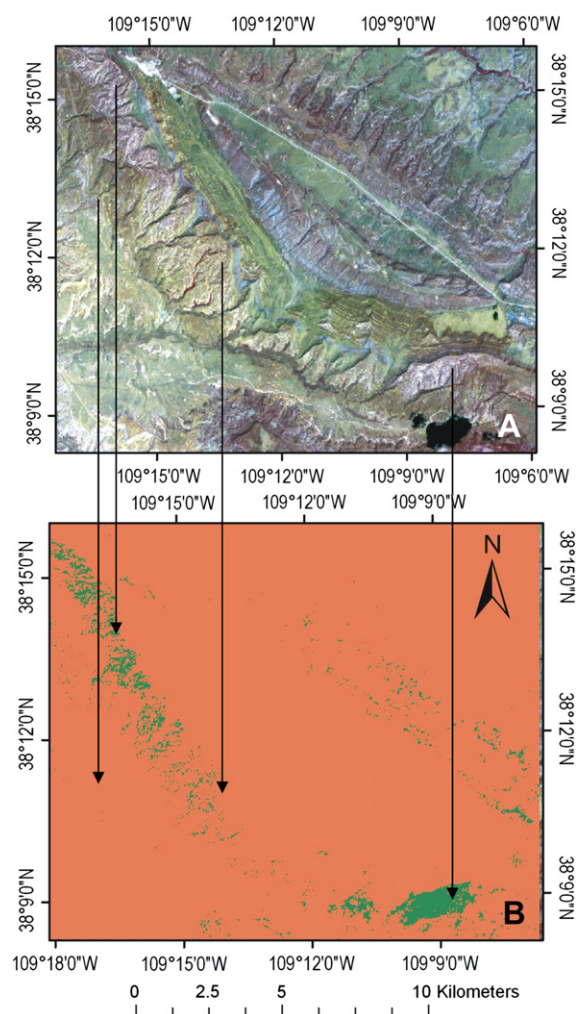


Fig. 5. (A) ASTER 3-2-1 (RGB) image of Lisbon Valley (subset), and (B) is the result of supervised classification of the same area. The green colored areas in B represent the part of the Wingate Sandstone classified as altered (bleached). The arrows connect the same points in (A) and (B) and show the exposed Wingate Sandstone, both altered and unaltered.

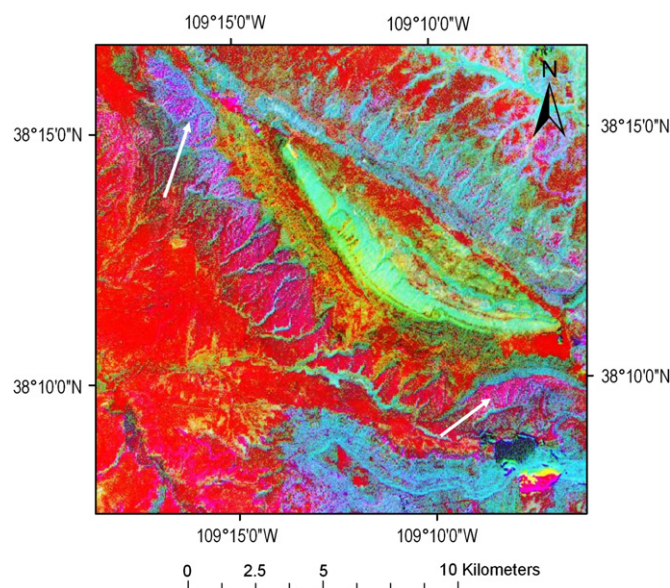


Fig. 6. The map of the Lisbon Valley area represented with the PCA short-wave infrared part of the electromagnetic spectra. Band combination used is (RGB) 1-2-3. Arrows point out the light pink color at the northwest and southwest part of the Wingate Sandstone surface exposure that represents the altered areas.

useful because it not only differentiated between altered and unaltered parts of the Wingate Sandstone, but also showed small differences between the Wingate and Navajo sandstones. The Navajo Sandstone is exposed in the study area as a dark, dull pink-reddish sandstone located stratigraphically above and to the west of the bleached Wingate Sandstone in the northwest part of the Lisbon Valley anticline. The altered Wingate strata are exposed as light pink, which differs from the Navajo Sandstone by its vividness and greater reflectance. These results also show a gradual change within bleached areas of the Wingate Sandstone. The southwest and northwest parts of the Wingate Sandstone in the Lisbon Valley are both altered, but the rocks in the southwest part show a higher intensity of alteration compared to the northwest areas (as indicated by a change of color).

The third processing technique of fusion of SAR data and an ASTER image utilized two PC Spectral Sharpening techniques: one sharpening technique was used on the PCA result of the VNIR part of the ASTER image spectra and radar (Fig. 7A), and the other on VNIR bands of an ASTER image and radar data (Fig. 7B). The fusion of both datasets was used in order to see if some further differentiation of the bleached areas was possible. The results show that the fusion of visible-near infrared ASTER bands and SAR data can be used to distinguish between different alteration sites in the Wingate Sandstone in the northwest and in the southwest part of the Lisbon Valley anticline, as well as small differences between the bleached Wingate and Navajo strata (Fig. 7B).

4.2. Geochemistry results

Hydrocarbon-induced rock alteration can be verified by the presence of some minor and trace elements, especially nickel (Ni) and vanadium (V), in concentrations that are characteristic of geochemical halos that form over oil and gas fields. Hydrocarbon microseepage creates a reducing zone in the soil and rock column above the leaking reservoir at depths closer to the surface than would be expected in the absence of seepage (Schumacher, 1996).

The abundances of nickel and vanadium (Table 2), determined using ICP-AES, are very close to and higher than the average for these elements throughout the western USA oil fields (Yen, 1975; Valkovic, 1978). Nickel concentrations in bleached Wingate

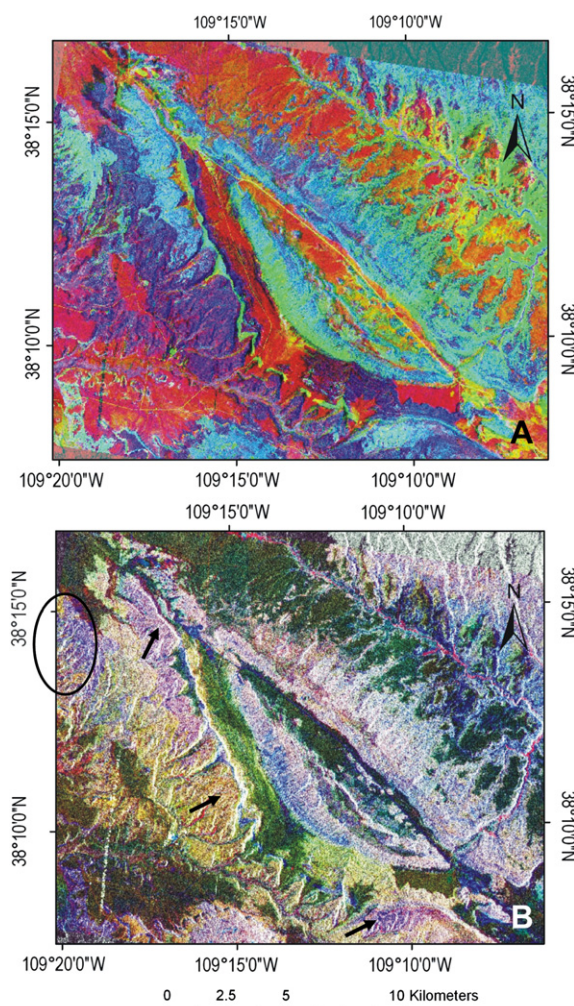


Fig. 7. The map of the Lisbon Valley area represented with (A) fusion of PCA VNIR part of the ASTER image spectra and radar JRES, and (B) fusion ASTER VNIR image and radar data. Black circle in (B) shows the Navajo strata, whereas the arrows show the extent of both altered (pink-purple) and unaltered (yellowish-red) Wingate Sandstone.

Sandstone samples range from 8.55 ppm to 41.55 ppm, whereas vanadium has concentrations from 7.20 ppm to 42.51 ppm in the same rocks. It has been reported that the average concentration of nickel in 23 different US crude oils is 10.2 ppm whereas vanadium has the average concentration of 38.24 ppm in the same oils (Yen, 1975). Most trace element concentrations are also higher than reported in various sandstones throughout the USA (Table 3). The accumulation of those elements, as well as chromium (Cr), cobalt (Co), zinc (Zn), copper (Cu), and strontium (Sr), were probably the result of transportation within hydrocarbons to, and precipitation within, the altered levels due to the reducing environments caused by hydrocarbon microseepages.

Table 2

Minor element concentrations in the bleached samples from Wingate Sandstone

Sample	Cr (ppm)	Ni (ppm)	Co (ppm)	Zn (ppm)	Cu (ppm)	V (ppm)	Sr (ppm)	Ba (ppm)
49a	2.33	8.55	2.68	13.68	5.84	26.76	85.54	319.31
50	2.41	41.55	64.32	33.97	28.05	26.17	63.82	294.92
52	8.43	26.58	3.70	72.76	45.17	42.51	95.44	386.35
53	0.95	17.87	7.13	45.92	18.99	36.45	81.64	416.34
58	BDL*	37.11	1.12	63.15	22.53	7.20	40.30	227.75
59	BDL	8.99	BDL	33.47	6.52	9.37	44.37	255.60
61	BDL	10.68	1.85	27.60	19.60	11.47	49.58	277.94

BDL*, below detection level.

Table 3

Comparison of minor element concentrations between altered Wingate Sandstone and sandstones throughout the United States

Element	Concentrations in altered Wingate sandstones [ppm]	Concentrations in sandstones from various locations in the US [ppm] ^a
Ni	8.55–41.55	1.2–18
V	7.20–42.51	5.3–38
Zn	13.68–72.76	5.2–31
Cr	0–8.43	2.0–39
Co	0–64.32	1.6–7.4
Cu	5.84–45.17	1.2–8.4
Ba	227.75–416.34	38–170
Sr	40.30–95.44	13–99

^a From Brownlow (1979).

Thin section studies of altered parts of the Wingate Sandstone reveals the presence of clay content in modal percents of 9.6–14.9% (Table 4). The shape and appearance of clay minerals, along feldspar grain margins or around them, suggests that their presence is a direct result of feldspar alteration. Carbonate cement probably occurs at the sites of former hematite cements. This is suggested by the fact that all unaltered, red Wingate Sandstone has previously been reported in the literature to have hematite cement (Segal et al., 1984, 1986). ICP-AES analyses showed a significant amount of CaO present in the bleached Wingate Sandstone samples (Table 5), in concentrations that were generally higher than that of hematite.

Reflectance curves were observed for the spectral interval from 350 nm, which is the visible part of the spectrum, to 2500 nm (near infrared). All samples analyzed using spectroscopy showed characteristic absorption features at approximately 400, 1400, 1900, and 2200 nm of wavelength (Fig. 8), which indicate the presence of iron ions (at 400 nm), hydroxyl ions, and clay minerals (1400, 1900, 2200 nm). The range from 500 to 1000 nm without any major absorption features corresponds with the spectral curve characteristic for the mineral calcite. However, calcite can also be characterized by the spectral absorption response at around 2200 nm (Beitler et al., 2007), but here it can be masked by clay content due to their similar absorption responses. Still, the presence of both clay and calcite has been confirmed with thin section analyses.

5. Interpretation of results and discussion

The influence of hydrocarbons leaking from their underground reservoir into the overlying rocks has been addressed in the literature many times (Donovan, 1974; Segal et al., 1984, 1986; Schumacher, 1996, etc). Bleaching of sandstones, a type of micro-seepage-related alteration, has been observed above several hydrocarbon reservoirs (Segal et al., 1984; Schumacher, 1996; Beitler et al., 2003). Laboratory experiments have also demonstrated the ability of hydrocarbons to bleach red beds (Surdam et al., 1993), and

Table 4

Table lists percentages of mineral abundances in the Wingate Sandstone

Sample number	Quartz	Feldspars	Clay	Rock fragments	Other
49b	59.9	23.9	13.4	0.7	2.1
50	59.9	22.4	11.8	2	3.9
52	53.7	26.8	14.1	2.7	2.7
53	60	20.6	12.9	1.3	5.2
55	53.9	26	14.9	2.6	2.6
57	63.5	20.8	10	3.8	1.9
58	62.7	22.3	11.2	1.9	1.9
59	65.4	19.6	13.1	1.3	0.6
60	56.1	29.5	9.6	1.8	3

Volcanic and chert rock fragments were observed in thin sections. As for the mineralogies grouped in category "Other", they mostly consist of a few grains of pyrite, siderite, micas (muscovite and biotite), and heavy minerals.

Table 5

Major elements concentrations in weight percent in samples from the Wingate Sandstone

Sample	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	TiO ₂	MnO	P ₂ O ₅	Na ₂ O	K ₂ O	Total
49a	86.72	5.27	0.82	0.45	3.15	0.24	0.06	0.07	0.98	2.18	99.93
50	89.74	6.04	0.80	0.28	0.10	0.18	0.01	0.04	0.47	2.47	100.14
52	86.11	5.18	1.09	0.44	3.90	0.34	0.07	0.08	0.73	2.69	100.62
53	86.86	6.50	0.95	0.37	1.43	0.24	0.02	0.06	0.66	2.76	99.85
58	95.75	2.83	0.30	0.11	0.22	0.04	0.00	0.02	0.18	1.51	100.96
59	93.51	3.06	0.51	0.14	0.65	0.08	0.02	0.03	0.18	1.56	99.73
61	91.53	4.31	0.68	0.31	0.06	0.10	0.00	0.04	0.30	1.64	98.96

Fe₂O₃ and CaO are represented in bold to emphasize their respective concentrations.

geochemical modeling has supported these experiments and shown that methane can reduce and mobilize iron (Parry et al., 2004). Additionally, bitumen veins have been observed in bleached rocks along the Moab fault in Utah (Chan et al., 2000). This present research was designed to demonstrate changes in the Wingate Sandstone in Lisbon Valley, Utah, and test the hypothesis that those changes came as a result of contact with hydrocarbons that came from the underlying petroleum reservoirs.

Remote sensing techniques have shown that the Wingate Sandstone does not have uniform compositional changes throughout its exposure in Lisbon Valley. Altered, bleached rocks have been mapped along the southwest and the northwest part of the Lisbon Valley anticline, whereas in between these two areas unaltered sandstone crops out. Altered areas have been mapped using the knowledge gained from previous field work (Petrovic, 2006), where some bleaching in otherwise red sandstones was noticed. Spectral endmembers of grayish sandstones were chosen for the remote sensing classification. The location of alteration, as well as its intensity, is related to the Lisbon Valley fault zone that is dissecting the crest of the anticline (Thorson and MacIntyre, 2005). Faults are excellent pathways for leaking hydrocarbons, and as observed in Lisbon Valley, the altered areas are located next to the fault. The alteration in the southwest is the closest to the main Lisbon Valley fault, and unaltered sandstones occur further away from it. This juxtaposition is the main reason to propose that the Lisbon Valley fault is the main leakage pathway.

The use of elemental, mostly trace elements, concentrations in surficial petroleum investigations relies on the principle that hydrocarbons, or inorganic components associated with the oil, are continuously migrating to the surface (Levinson, 1980). Nickel and vanadium concentrations measured in the bleached Wingate Sandstone samples show values unusually high for sandstones. Typical Ni concentrations in sandstones are around 2 ppm, and V are around 20 ppm (Levinson, 1980), whereas bleached Wingate sandstones have Ni concentrations of 8.55 ppm to 41.55 ppm, and V concentrations from 7.20 ppm to 42.51 ppm in the same rocks. Other trace element concentrations from altered samples in this study were also mostly higher than common for sandstones (Table 3). However, they are not as high as they would be if they came from seawater or hydrothermal alterations, where they range from hundreds to thousands of ppm (Gibson et al., 1996). Duchscherer (1984) reports that V, Cr, Mn, Ni, Co, Cu, Mo, U, Fe, and Zn, are among minor and trace metals found as geochemical halos over oil fields in Texas and Montana, United States. Their incorporation into sediments above oil fields is mostly controlled by the reaction of clay minerals with soluble organic matter (Duchscherer, 1984). Also, both Ni and V are immobile in reducing environments, except in gley-related environments (Levinson, 1980), which were not observed in the Lisbon Valley area. Consequently, we believe that the occurrence of Ni and V in high concentrations in the altered Wingate Sandstone is related to the reducing environments associated with seepage of hydrocarbons through these rocks.

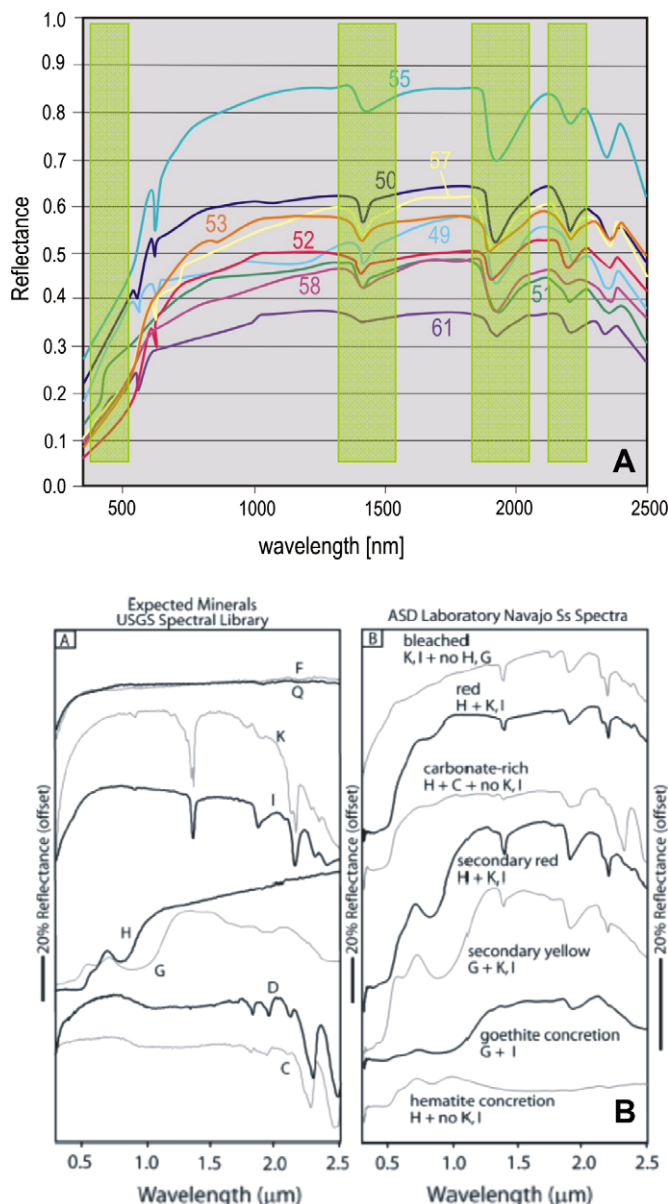


Fig. 8. (A) The reflectance values for several Wingate Sandstone samples. Diagnostic clay, hydroxyl ion, and iron absorption features of altered samples are identified by their patterns within the green rectangles. Numbers 49–61 within the graph represent the number of the analyzed Wingate Sandstone samples. (B) The reflectance values of different Navajo Sandstone samples showing the spatial change in diagenetic mineralogy related to fluid seepage, F, potassium feldspar; Q, quartz; K, kaolinite; I, illite; H, hematite; G, goethite; D, dolomite; C, calcite (Beitler et al., 2007). Both sets of graphs are shown here for comparison purpose. Reflectance curves for altered Wingate (A) and Navajo (B) sandstones are very similar, which indicates that they have very similar mineral compositions.

Thin section analyses were also performed on bleached rocks and they showed the absence of hematite, which was the original cement in the unaltered, red Wingate Sandstone (Segal et al., 1984, 1986). Some pyrite crystals have been observed, indicating that the reducing environment has caused the transformation of hematite to pyrite. Calcite cement was observed and is believed to have replaced the hematite. Significant amounts of clay minerals are also present, mostly surrounding feldspar grains. Feldspars show a significant degree of alteration, with clay at their grain margin, and along the cleavage planes. The feldspars contain cloudy regions, and in some places those cloudy regions grade into well-developed secondary clay minerals. Clays can be formed by different types of

feldspar alteration, namely chemical weathering, hydrothermal alterations, and reducing environments. Trace element concentrations (most significantly Ni and V) measured by ICP-AES analyses are higher than in sandstones, in general, but are lower than expected if produced by hydrothermal and weathering agents. Thus, the reducing activities remain the reasonable cause for the alteration of feldspars and formation of clays.

Spectroscopy confirmed the presence of clays, as well as some iron ions, hydroxyl ions, and calcite in the Wingate Sandstone. What is even more interesting, when spectral curves of the altered Wingate Sandstone are compared to altered and unaltered Navajo Sandstone (Beitler et al., 2007, Fig. 8A and B, respectively), the spectral reflectance curves from both altered sandstones match almost identically, indicating that they have very similar compositions. Beitler et al. (2007) showed in their study the potential of spectroscopy in evaluating the complexity of spatial change in diagenetic mineralogy related to fluid seepage. Thus, the systematic observation of mineralogical change related to hydrocarbon seepage was observed in the Wingate Sandstone.

6. Conclusions

Hydrocarbons leaking from subsurface petroleum reservoirs can create a reducing environment in the stratigraphic columns and soils above the reservoirs, and thus induce alteration of the rock and soil. This study combined different remote sensing and geochemical tools to detect, map, and analyze rock alteration caused by leaking hydrocarbons in Lisbon Valley, Utah. It is believed that the main pathway for the leaking hydrocarbons was the Lisbon Valley fault, which cut its way through the center of an anticline, and other smaller faults. This assumption is based on the proximity of altered zones to the fault zone. This research supports the hypothesis that the alteration in the Wingate Sandstone is the result of hydrocarbon microseepages, based on the geochemical properties of the bleached rocks.

All remote sensing processing techniques used for ASTER image classification, and its fusion with SAR radar data, were successful in mapping the alteration zones. The best results were obtained from the supervised classification and the fusion of ASTER and radar data. Differences within the Wingate Sandstone in Lisbon Valley, Utah, in the form of bleached beds were detected on the southwest and northwest part of the Lisbon Valley anticline, whereas the middle part appears to be unaltered.

Point counting in thin sections showed a presence of significant amounts of clay minerals (9.6–14.9 %), and the lack of hematite cement in altered or bleached parts of the formation. The distribution of clay minerals suggested that they were formed by alteration of different feldspar minerals. Some feldspars showed a significant degree of alteration, with clay along the cleavage planes and edges. This formed a cloudy region, which in some places graded into well-developed secondary clay minerals. Also, spectroscopy showed that selected bleached samples from the Wingate Sandstone had significant abundances of clays, hydroxyl ions, and ferric ions, as well as calcite. The ICP analyses agreed with the thin section analysis with regard to the abundance of dominant minerals. It also revealed the presence of some minor and trace elements (nickel, vanadium, zinc, chromium) in concentrations that are in the range similar to their abundance in oil fields.

Results presented in this study affirm that bleaching and other large-scale alterations have been caused by leaking hydrocarbons. Remote sensing techniques proved to be successful when it came to distinguishing between altered and unaltered Wingate sandstones, as well as distinguishing the degree of alteration in some areas. If further analyses fully confirm this concept, then this type of research can be used as a new tool for petroleum investigations and explorations in areas where field work is difficult.

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