HYPERSPECTRAL HYDROCARBON MICROSEEPAGE DETECTION AND MONITORING: POTENTIALS AND LIMITATIONS

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Abstract

Oil and gas reservoirs leak. As a result large quantities of oil and gas from these reservoirs reach the surface forming seeps. When visible with the human eye we refer to macroseeps, else to microseeps. Macroseeps, particularly offshore, have been extensively studied. Microseeps are less well studied. Seeps are relevant to the oil and gas industry as a potential source of information for exploration. In addition, seeps are a source of methane emission and as such contribute a large but yet un-quantified amount of this gas to the global budget. Methane is a greenhouse gas. Hydrocarbon microseepage gives rise to expressions at the Earth surface in form of: (1) detectable trace concentrations of gasses (mainly ethane and methane), (2) mineral alteration of soils, and (3) anomalous spectral response in vegetation. Off shore, oil macroseeps can be seen forming slicks on the water surface detectable using radar imagery. Within the water column, the upward seeping gas produces bubbles that can be detected using sonar. On shore, seismics provides a means of visualising subsurface chimneys along which oil and gas migrate to the surface. At the surface, geochemical soil gas analysis provides insights into the nature and composition of the gas. High spectral resolution spectroscopic measurements in the field and from airborne or spaceborne imaging devices may potentially be used to detect and monitor hydrocarbon microseepage using mineral alteration (detection) and gas emission (monitoring using emission spectra).

1 Introduction

Oil and gas reservoirs leak. Small but measurable quantities of oil and gas migrate to the surface through nearly vertical chimneys as a result of reservoir leakage (Figure 1). Hydrocarbon seepages are seeping hydrocarbons moving to the surface through their seal rocks, while (hydrocarbon) microseepages are seeping (invisible) light hydrocarbons that can only be detected at the surface chemically. Offshore, radar has been proven to be a valuable remote sensing tool for mapping oil on the surface of ocean waters. Recently, sonar has been used to detect microseepage offshore. Studying surface occurrences of microseepages onshore may be a prospective tool for oil and gas exploration. Two approaches may be followed: direct detection and indirect detection. Direct detection is defined as the detection of either oil pools or mineral alteration related to seepages. Methods of indirect detection focus on secondary effects resulting from seeping light hydrocarbons to the surface. These relate to changes in the vegetation structure reflected in spectroscopic data acquired in the field or by airborne/spaceborne instruments. Hydrocarbon microseepage studies are relevant not only to the oil industry as a tool for exploration for oil, but also from an environmental perspective: methane, one of the seeping gases, is a major contributor to the greenhouse effect. It is unclear at present what the global contribution of microseepage is to the natural methane production annually. However local estimates show that this must be significant, for example venting in the North Sea basin has been estimated to release2.6 x 10^{12} g methane per year into the water column (Hovland & Judd, 1988).

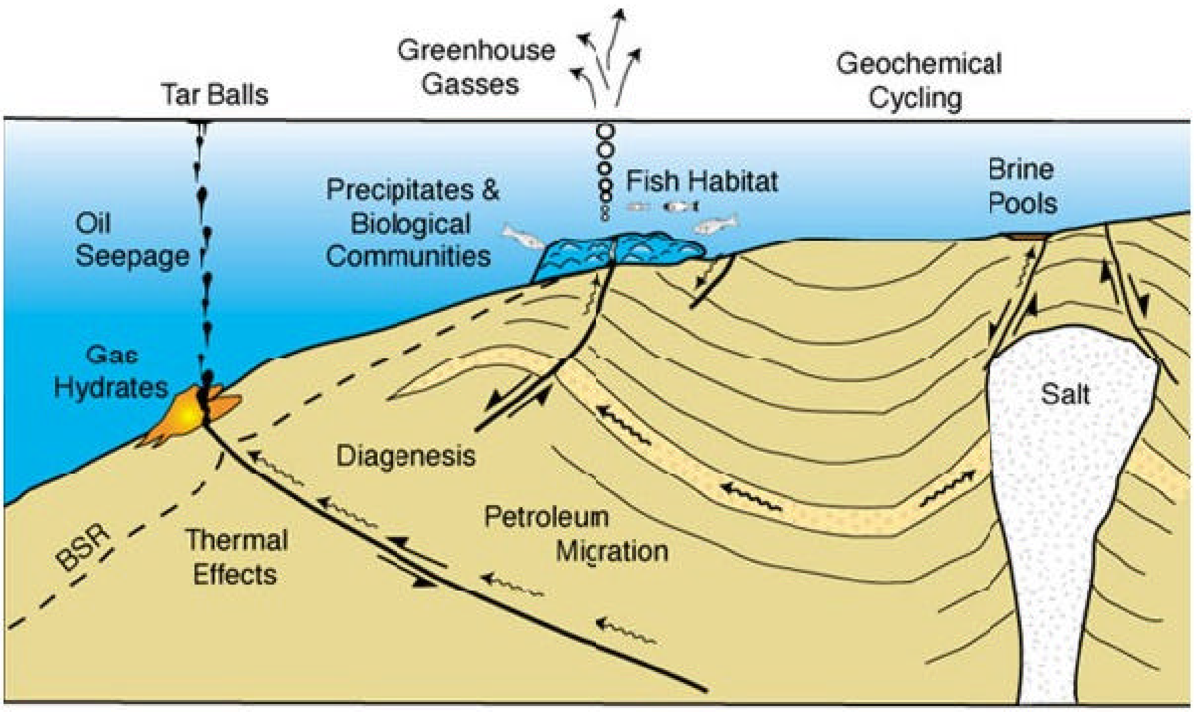

Figure 1. Schematic example of microseepage (after the Margins homepage).

Worldwide, there is a correlation between seeps and earthquake activity, where seeps occur predominantly in areas that are tectonically active. The amount of seepage (ppm methane/ethane) potentially is related to the pressure in reservoirs which is related to hydrostatic pressure and changes in lithospheric stress. Thus in natural seepages, a relation between the amount of seeping gas and stress could be envisaged.

2 Geochemistry of hydrocarbon microseeps

Seepage is a near vertical process resulting in migrating hydrocarbons along chimneys. Vertical migration through the strata has been attributed to at least four mechanisms: effusion; diffusion; solution and buoyant micro-gas- bubbles. Effusion as a free hydrocarbon gases is thought to be the principal mechanism leading to macroseepage. It arises as a result of the very large pressure differential that exists across a petroleum reservoir. Diffusion of hydrocarbon gases that are usually dissolved in groundwater has been observed through seemingly impermeable barriers. This form of migration is thought to contribute to microseeps. Also dissolved low molecular weight hydrocarbons in groundwater migrate through capping shales as a result of hydrodynamic or chemical potential drive. Vertical ascent of ultra-small (colloidal size) gas bubbles through a network of inter-connected, groundwater-filled *microfractures* is advocated by many researchers. Researchers confirmed that connected networks of fractures, joints and bedding planes serve as channels for micro-bubble migration between hydrocarbon reservoirs and the surface. Buoyant colloidal gas bubbles are readily displaced upward at rates up to several millimetres per second. This fast ascent explains the rapid development of light hydrocarbon anomalies in soil gas over newly-filled gas storage reservoirs, and their rapid disappearance after a reservoir is depleted. Gasses, in particular methane cause pronounced absorption features in radiance spectra which can potentially be identified using (imaging or field) spectrometer data.

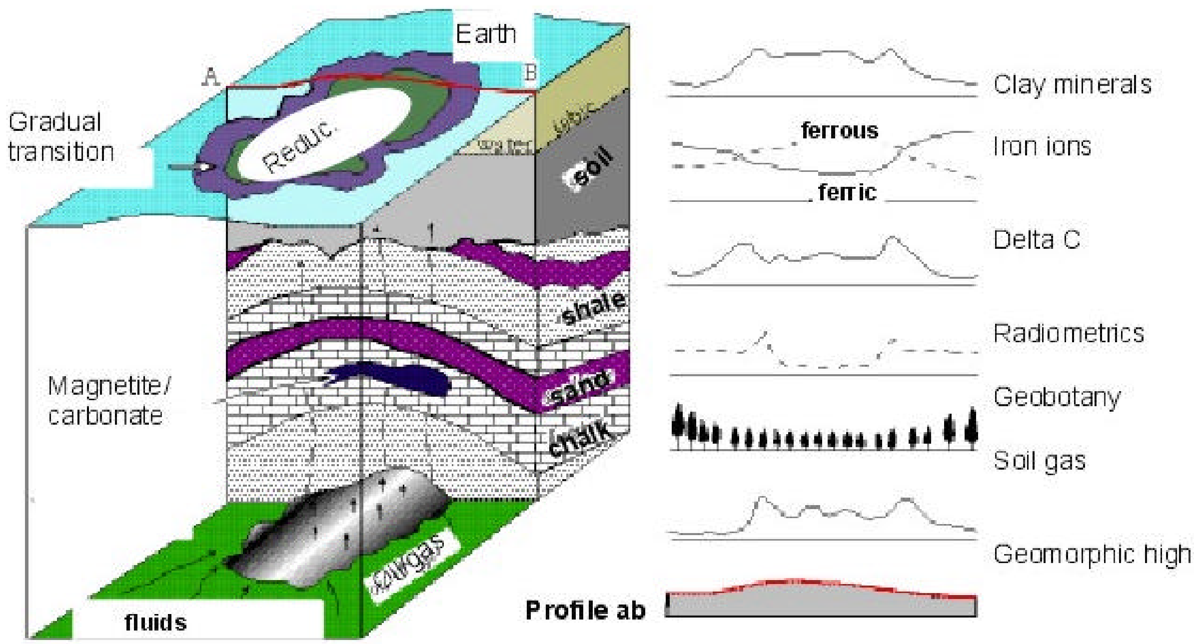

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Figure 2. Typical geochemical scheme around microseepage affected areas.

Long-term leakage of hydrocarbons can establish locally anomalous redox zones that favour the development of a diverse array of chemical and mineralogical changes (Saunders et al. 1999; Schumacher & Abrams 1996). The bacterial oxidation of light hydrocarbons can directly or indirectly bring about significant changes in the pH and Eh of the surrounding environment, thereby influencing mineral stability and chemical reactivity. Such oxidation in the chimney above a leaking petroleum accumulation leads to dissolution or precipitation of minerals and the mobilisation or immobilisation of certain elements in the chimney, which thereby becomes mineralogically and chemically different from laterally-equivalent. Figure 2 shows some of the expected processes occurring around sites affected by microseepage. The resulting alterations include: the formation of calcite, pyrite, uraninite, elemental sulfur, and certain magnetic iron oxides and iron sulfides; bleaching of red beds; clay mineral alteration; electrochemical changes; radiation anomalies; geomorphic anomaly; the edge anomaly of adsorbed or occluded hydrocarbon in soils and Delta C (ferrous carbonate); and biogeochemical and geobotanical anomalies (Durscherer, 1986). The presence at surface of bleached and discolored red sandstones above petroleum accumulation has been widely noted. Bleaching occurs whenever acidic, reducing fluids dissolve the ferric oxide (hematite) that gives the red bed its characteristic colour. The acidic conditions resulting from the oxidation of hydrocarbons in near-surface soils and sediments promotes the diagenetic weathering of feldspar to clay and the conversion of smectite clay to kaolinite. The kaolinite thus formed remains chemically stable unless the environment is changed. Ferrous carbonate, also called "Delta C" show highs above the edges of hydrocarbon accumulations. The bicarbonate and carbonate chemistry of calcium and iron may provide a viable explanation for edge-leakage of Delta C iron carbonate anomalies. Many of these alteration minerals can be mapped using spectroscopic data (Van der Meer, 1999). Problems in direct detection of microseepage via these alteration schemes is that it is difficult to separate background mineralogy from alteration mineralogy. Furthermore, the proposed alteration schemes by Saunders et al. (1999) are not clearly based on sedimentary or petrological environments, but they compose a more general classification which needs to be further refined.

Geobotanical anomalies occur as a results of the effect of light hydrocarbons on the growth of vegetation. Reflectance properties of vegetation in the visible part of the spectrum are dominated by the absorption properties of photosynthetic pigments of which chlorophyll, having absorption at 0.66 and 0.68 *mm* for chlorophyll a and b, respectively, is the most important (Elvidge, 1990). Changes in the chlorophyll concentration produce spectral shifts of the absorption edge near 0.7 *mm*: the red edge (also termed as inflection point, the point of maximum slope on the reflectance spectrum of vegetation between red and near-infrared wavelengths, defined as the wavelength of maximum $dR/d\lambda$. This red edge shifts toward the blue part of the spectrum with loss of chlorophyll, and shifts towards the red part of the spectrum with increase of chlorophyll. The results are (1) a decrease in the height of the infrared shoulder due to structural damage; (2) an increase in the reflectance at the chlorophyll absorption maximum due to decreased leaf chlorophyll; and (3) a shift in the position of the red edge towards shorter wavelengths. Several approaches to mapping the red-edge and shifts in the position (Wessman et al., 1988; Horler et al., 1983).

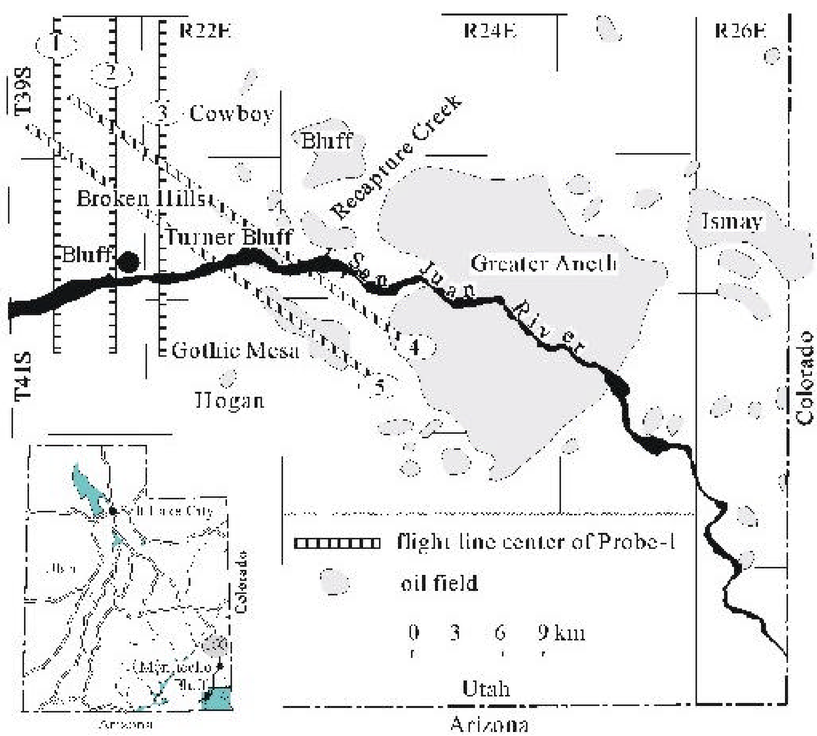

Figure 3. Flight lines and oil fields at Bluff. Probe data from line 5 used in this study.

3 Hyperspectral *detection* of hydrocarbon microseepage

3.1 Hydrocarbon microseepage induced alteration mapping

In a sparsely vegetated semi-arid area where reddish sandstone and mudstone dominate the surface in southeastern Utah, red bed bleaching is a common phenomenon associated with hydrocarbon microseepage. Near the area of Bluff, the Probe-1 imaging spectrometer (Figure 3) data was acquired to map rocks associated with this phenomenon. The signal-to-noise ratio of the data was evaluated to assess the ability of the sensor. Wavelength calibration, radiometric calibration and atmospheric calibration were performed to the data set to obtain reflectance data. Through spectral analysis of the rock units, it was found that the gray-green rocks (possibly bleached) have distinct spectral features that can be separated from those of the reddish rocks (unaltered). Spectral angle mapping was used to classify the seven exposed units from the Probe-1 data. It was possible to distinguish the gray-green rocks that might be associated with hydrocarbon microseepage using the Probe-1 data (Figure 4).

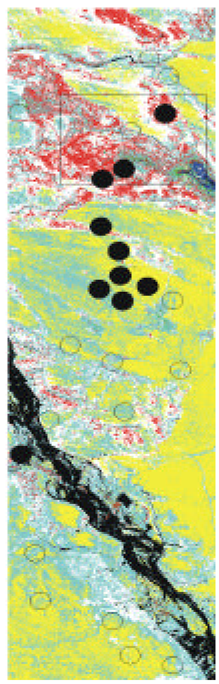

Figure 4. SAM classification of red bed bleaching due to microseepage from Probe data. The red pixels are altered, the light blue are unaltered red-beds. Solid dots are producing wells, circles are dry wells.

3.2 Hydrocarbon microseepage and geobotany

Several studies have indicated a relationship between red edge inflection point and microseepage exists (Bammel & Birnie 1984) and with other factors resulting in vegetation stress (Collins et al. 1983) and that this can be mapped (Segel & Merin, 1989). We have studied vegetation spectra (Yang et al. 1999) in field spectra and imaging spectrometer data in the Weibei basin (8 km north of the city of Changyi, PR China) where oil reservoirs are structurally controlled and found in Eocene sandstones capped by mudstones of the same age/formation. Over two transects (Figure 5) known to extend over various oil/gas and oil/water contacts and faults both field spectroradiometer measurements of soil and vegetation (with a GER 3700) and in-situ soil gas measurements were taken. The vegetation investigated is a mono-cultural crop composed of spring wheat. Statistical analysis of the red-edge position of the vegetation spectra (indicative of the chlorophyll production and "healthiness" of the plants) versus the soil gas data (indicative of occurrences of microseepages) shows good exponential relations (Figure 6). The relationships found were further tested on imaging spectrometer acquired with the Modular Airborne Imaging Spectrometer operated and calibrated by the Chinese Academy of

Sciences. We mapped the red edge position in relation to field measurements of soil gas and found that microseepage acts as a fertiliser to the growth of the local crops (Yang et al. 2000).

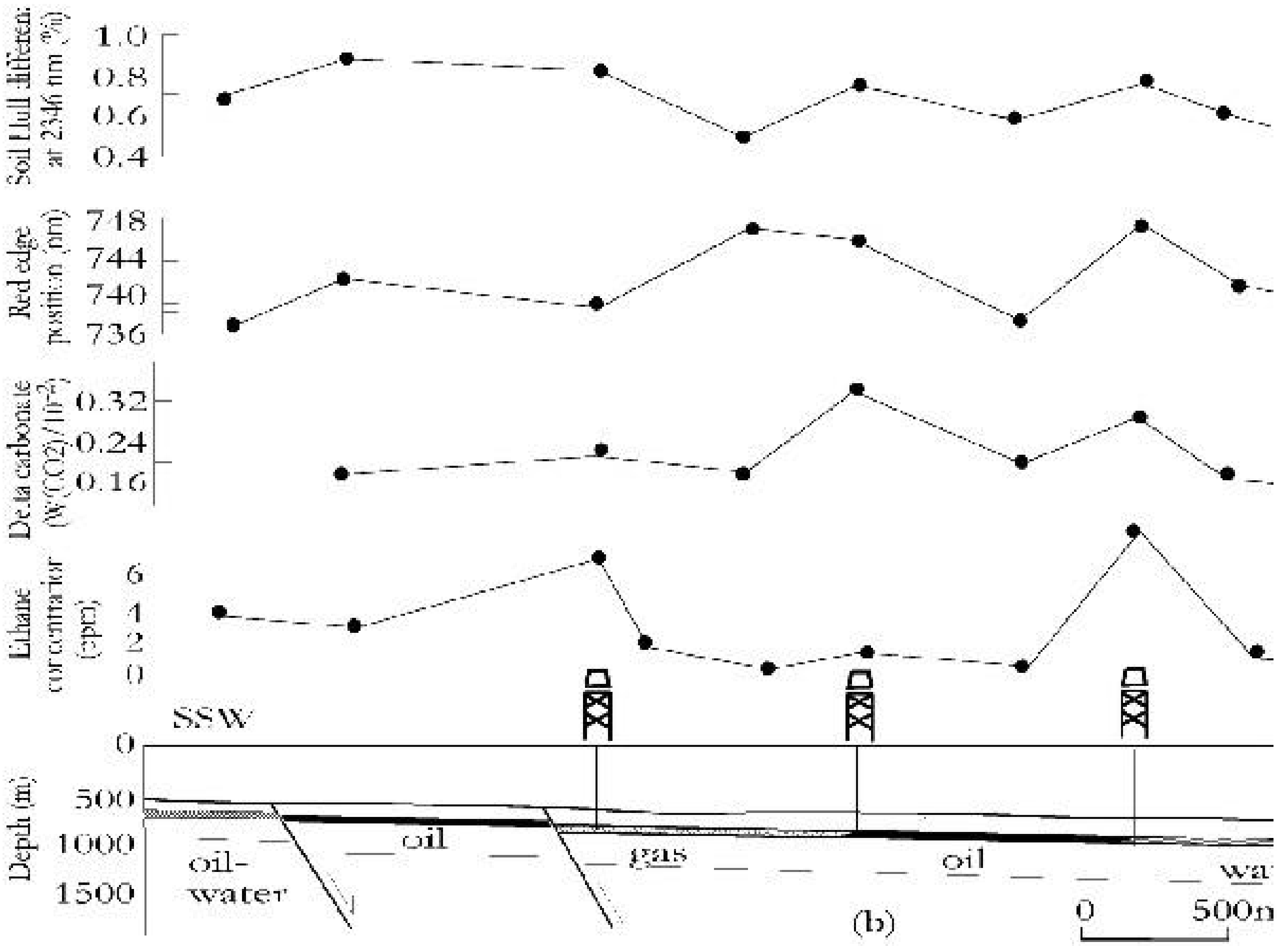

Figure 5. Example of a transect in the Weibei area of China with soil geochemistry and results of spectral analysis plotted.

3.3 Future direction: *monitoring*

Our future research centers on monitoring of hydrocarbon microseepage using the Baku area of Azerbaidzjan as a study site. Field measurements of gas seepage over time will be collected to gain insight into the fluxes of emissions, the stability of these flows and the changes in time. In addition, detection of surface alteration using remote sensing data in combination with surface geochemistry will provide a means of extrapolating results to larger (spatial) areas. Investigation of the surface and subsurface geologic record will provide the necessary backup for geological modeling of the observed microseepage records.

Geochemical measurements, in particular soil gas analysis of ethane and methane, taken at the Earth’s surface can aid in locating anomalous areas in relation to hydrocarbon microseepage. These measurements are time consuming, labour intensive and expensive. A remote sensing approach to locate anomalous areas could serve to better target for oil exploration and geochemical/geophysical prospecting and has the advantage of being reproducible in time and over large areas. Offshore detection of macroseepages using remote sensing has been proven very successful, onshore detection has been relatively poorly investigated. Not only can remote sensing, in particular high spectral resolution imaging, detect hydrocarbon microseepage affected areas, it may also be a source of information for monitoring change. Quigley et al. (1999) demonstrated a decrease in natural marine hydrocarbon microseepage as a result of oil production and subsequent reduction of hydrostatic pressure in the reservoir. These authors used sonar imagery acquired in 1973 and 1995 and mapped from this the change in aerial extent of the seepage area. On shore, chimneys are seen on seismic data (possibly also on ground radar data) and methane produces significant absorption features in reflectance and emission spectra. Using the depth of these absorption features, potentially a method can be derived to quantify the amounts and concentrations of the gases involved. Similar techniques have been developed in remote sensing to map atmospheric water vapor and SO2. The results from field spectral surveys over several areas known to contain hydrocarbon microseeps will be validated using soil gas analysis. The total area affected by the microseepage can be determined by investigating the surface mineral alteration pattern using imaging spectrometer data. We propose to use data from the ASTER sensor on the TERRA platform for this purpose. A data acquisition request has been submitted to NASA requesting the necessary image data. The results using present day remote sensing and subsurface data can be compared with older subsurface data sets to investigate changes over longer time spans. We also plan to conduct field measurements over several microseeps to study the differences in nature of these natural seeps, and we plan to conduct measurements during the time of the project to investigate whether the microseeps are stable or whether changes can be observed. Potentially these changes could be linked to changes in stress state the reservoir.

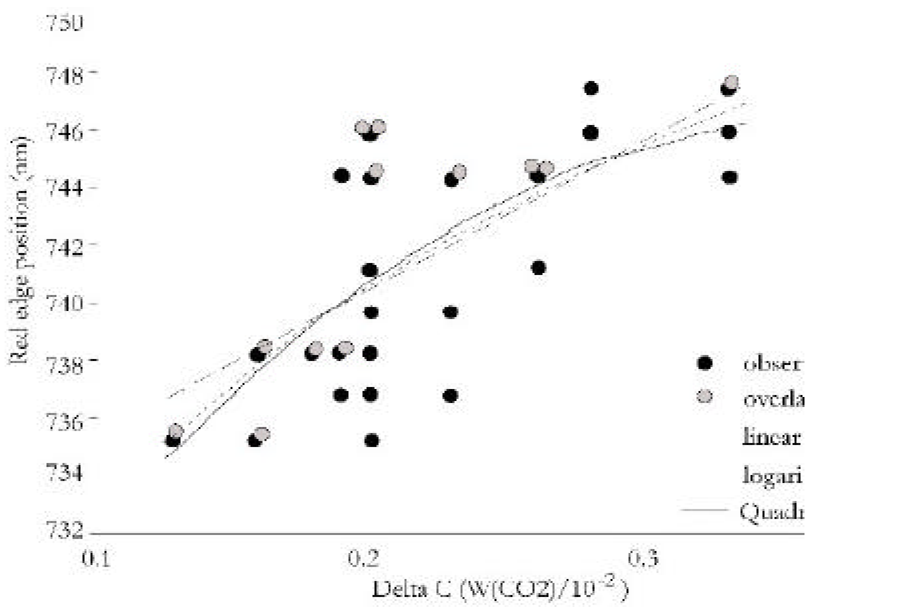

Figure 6. Correlation between delta C (indicator for microseepage) and the red edge showing moderate correlation (R2=0.6).

4 Conclusions

Oil and gas reservoirs leak through their impermeable seal and along faults cross-cutting the reservoir. As a result, light hydrocarbons migrate to the surface at seepage sites, where anomalous high concentrations of methane and other gasses can be measured. Hydrocarbon microseeps are of interest to the oil industry, and pose an environmental treat as methane is one of the most important (after CO2) gas contributing to the greenhouse effect. In this paper, we demonstrate ways to *detect* areas of hydrocarbon microseepage both in vegetated as unvegetated terrains using hyperspectral data. Our future research is directed toward quantifying the emission fluxes of methane using field surveys and spectroscopic modelling with radiative transfer codes. Combining the areal extent of the seepage with the emission fluxes should provide insight into the contribution of methane from seeping oil and gas reservoirs to the greenhouse effect.

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References

Bammel, B.H., and Birnie, R.W., 1994. Spectral response of big sagebrush to hydrocarbon-induced stress in the Bighorn Basin, Wyoming. *Photogrammetric Engineering and Remote Sensing*, 60, 87-96.

Collins, W., Chang, S.-H., Raines, G., Canney, F. and Ashley, R.1983. Airborne biogeophysical mapping of hidden mineral deposits, *Economic Geology*, 78: 737-749.

Durscherer, W., 1986. The principle of delta carbonate geochemical hydrocarbon prospecting demonstrated. In: *Unconventional method IV*. Dallas, TX: Southern Methodist University Press, 14-16.

Elvidge, C.D., 1990. Visible and near infrared reflectance characteristics of dry plant materials. Int. J. Rem. Sensing 11: 1775-1795.

Horler, D.N.H., M. Dockray & J. Barber, 1983. The red edge of plant leaf reflectance. Int. J. Remote Sensing 4: 273-288.

Hovland, M. & Judd, A.G. 1988. Seabed pockmarks and seepages: Impact on geology, biology and the marine environment. London: Graham & Trotman, 293 pp.

Quigley, D.C., Hornafius, J.S., Luyendyk, B.P., Frances, R.D., Clark, J. & Washburn, L. 1999. Decrease in natural marine hydrocarbon seepage near Coal Oil Point, California, associated with offshore oil production. Geology, 27(11): 1047-1050.

Saunders, D.F., Burson, K.R. & Thompson, C.K. 1999. Model for hydrocarbon microseepage and related near-surface alterations. *AAPG Bulletin*, 83(1): 170-185.

Schumacher, D. and Abrams, A. A., 1996. Hydrocarbon microseepage and its near-surface expression. *AAPG Memoir 66,* ix.

Segel, D.B., and Merin, I.S. 1989. Successful use of Landsat Thematic Mapper data for mapping hydrocarbon microseepage-induced mineralogic alteration, Lisbon Valley, Utah. *Photogrammetric Engineering and remote sensing*, 55(8): 1137-1145.

Van der Meer, F. 1999. Physical Principles of optical remote sensing. In: *Spatial Statistics for Remote Sensing*, Stein, A., Van der Meer, F. & Gorte, B. (Eds.) Kluwer Academic Publishers, Dordrecht, pp. 27-40.

Wessman, C.A., Aber, J.D., Peterson, D.L., & Melillo, J.M., 1988. Foliar analysis using near infrared reflectance spectroscopy. Canadian Journal of Forest Research, 18: 6-11.

Yang, H., Zhang, J., van der Meer, F. & Kroonenberg, S.B. 1999. Geochemistry and field spectrometry for detecting hydrocarbon microseepage. *Terra Nova*, 10(5): 231-235.

Yang, H., Zhang, J., van der Meer, F. & Kroonenberg, S.B. 2000. Imaging spectrometry data correlated to hydrocarbon microseepage. *International Journal of Remote Sensing*, 21(1):197-200.