Review article

Remote sensing and petroleum seepage: a review and case study

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ABSTRACT

When reservoirs leak, varying quantities of oil and gas migrate to the surface as macroseeps, which are visible, and microseeps, which are invisible. This review article describes the mechanisms of seepage and the resulting surface manifestations in relation to optical high-resolution remote sensing data. Oil pools and tar deposits (macroseeps) often can be detected directly by remote sensing. Microseeps are more difficult to study using remote sensing, but they give rise to vegetation stress, and cause geochemical alterations in soil and rocks, which can be studied indirectly using hyperspectral sensors. An integrated methodology is presented to combine various geoscience and remote sensing datasets for seepage detection. A combination of red-edge modelling algorithms and spectral matching tools is identified that provides a validated technique for onshore microseepage detection. These remote sensing tools are not only important for petroleum exploration, but also have environmental implications because seeps emit greenhouse gases. A statistical data integration approach was developed based on Bayesian assumptions, which can be used to integrate hyperspectral remote sensing data, other satellite remote sensing data, and ancillary field geological and geochemical datasets, for modelling microseepage. In a case study from the Ventura basin (Santa Barbara) in Southern California, Probe-1 data from the 1998 Geosat Group Shoot are integrated with field and subsurface geological and geochemical data to predict possible sites of hydrocarbon microseepage.

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Introduction

Remote sensing or earth observation involves the measurement, from a distance, of radiation spectra reflected and emitted from the Earth’s surface. The Multispectral Scanning System (MSS), the Thematic Mapper (TM), the SPOT satellite, Radar systems, airborne multispectral scanning systems and airborne imaging spectrometers have routinely been used to provide imagery for regional and local geological mapping. Remote sensing has been of considerable interest to earth scientists in general and exploration geologists in particular. The basin-wide assessment of favourable areas for petroleum exploration is normally called the ‘direct detection method’ and has been carried out in many oil fields (Halbouty, 1980). The key to successful application of remote sensing technology lies in its integration with other exploration tools such as seismic, well, gravity and magnetic data. Many researchers (e.g. Lang et al., 1985ab) have also tried to use spectral information to detect those surface alterations that directly indicate the presence of hydrocarbons at depth.

This paper reviews the use of surface manifestations of oil and gas reservoirs to map the petroleum potential of an area, focusing especially on seepage of oil and gas to the surface along faults or imperfect reservoir seals. The visible products of such seepage – oil and tar deposits – are generally referred to as macroseeps, whereas the invisible gaseous products are referred to as microseeps, although all intermediate products do also occur. Abrams (1996) separates seeps into active and passive as he writes: ‘Areas where subsurface hydrocarbons actively seep in large concentrations within and above the surface marine sediments are called active seeps. When active seeps contain anomalous low molecular weight and high molecular weight hydrocarbons that may be visibly stain sediment cores, they are generally referred to as macroseeps. Areas where subsurface hydrocarbons are not actively seeping are called passive seeps. These seep zones usually contain low molecular weight hydrocarbon concentrations above normal background levels (microseeps).’

The present paper goes on to review the spectral properties of organic materials and explore the processes involved in the migration of oil and gas to the surface. After examining the high spectral resolution sensors presently available for studying the Earth’s surface, a case study is presented that combines petroleum geology data and remote sensing.

Although seeps (macro- and micro-) are important in prospecting for oil and gas, they are also sources of gases, such as methane and carbon dioxide,
which contribute to the greenhouse effect. Data on their emissions are potential inputs into global change models. However, the fluxes and quantities of gases emitted from seeps are at present unknown and no method exists with which to monitor them (Moore, 1999). Much research has been carried out on the detection and monitoring of offshore microseepage, but relatively little in the onshore environment. Local estimates suggest that global methane emissions are significant: for example, venting in the North Sea basin has been estimated to release $2.6 \times 10^{12} \text{ g CH}_4 \text{ yr}^{-1}$ into the water column (Moore, 1999).

A correlation exists globally between seeps and earthquake activity, where seeps occur predominantly in areas that are tectonically active (Moore, 1999). The amount of seepage (p.p.m. methane/ethane) potentially is related to the pressure in oil/gas reservoirs, which in turn is related to hydrostatic pressure and changes in lithospheric stress (e.g. Quigley et al., 1999; Whelan, 2000). Thus, in natural seeps a relationship between the amount of seeping gas and stress could be envisaged.

Critical issues for studies of fluid seeps at continental margins and for research on offshore seep detection and monitoring can be summarized as:

- the relationship between seeps and plate tectonics;
- fault pressures in relation to emission fluxes of ethane and methane;
- the flux of hydrocarbons seepage (which is difficult to measure because many seeps are small, episodic and ephemeral);
- quantifying the flux of fluids from the lithosphere into the atmosphere;
- the connection of subsurface fluid flow to surface seepage;
- the flux measurements and statistical models needed to extrapolate the measurements to global estimates of flux;
- the processes which create fluid-induced geomorphic features;
- a strategy for the study of seeps that includes seep detection, characterization of emission products, quantification of fluxes, and study of time variations.

Areas of oil and gas seeps show anomalies in, and are characterized by, anomalously high concentrations of ethane/ethene, propane/propane and methane. These anomalies can produce mineral alteration in soil and rock, radiometric anomalies, temperature anomalies and geobotanical anomalies (Tedesco, 1995). Two remote sensing 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 the seepage of light hydrocarbons to the surface (Yang et al., 1999), notably changes in the vegetation structure. In 1998, under the auspices of the Geosat Committee, a hyperspectral data acquisition with the probe-1 airborne imager was conducted over several targets in the western part of the USA. The present contribution uses results from data acquired over the Ventura basin (Santa Barbara, California) test site.

**Spectra of organic compounds**

Spectra of organic compounds are dominated by the C–H stretch. The C–H stretch fundamental occurs near 3.4 $\mu\text{m}$, the first overtone is near 1.7 $\mu\text{m}$, and a combination band occurs near 2.3 $\mu\text{m}$. The combinations near 2.3 $\mu\text{m}$ can sometimes be con-

*Fig. 1 [Transmittance spectra of organics and mixtures showing the complex absorptions in the C–H-stretch fundamental spectral region (King and Clark, 1989).]*
fused with OH and carbonate absorptions in minerals, especially at low spectral resolution.

Figure 1 shows some transmittance spectra of organics and mixtures highlighting the complex nature of the absorption bands in the mid-infrared where the C–H-stretch fundamentals occur. Figure 2 shows the reflectance spectra of montmorillonite, and montmorillonite mixed with super unleaded petrol, benzene, toluene and trichloethylene. Montmorillonite has an absorption feature at 2.2 μm, whereas the organics have a C–H combination band near 2.3 μm. The first overtone of the C–H stretch can be seen at 1.7 μm, and the second near 1.15 μm (King and Clark, 1989). The reflectance spectra of solid CO₂, CH₄ and H₂O are shown in Fig. 3. These reflect the approximate fingerprints for gas absorption mapping and emission.

**Hydrocarbon microseepage**

**Introduction**

Macroseepage is the visible presence of oil and gas seeping to the surface (documented in various parts of the world by Tedesco, 1995); microseeps are hydrocarbons seeping probably vertically or near-vertically from the reservoir to the surface. The best evidence for near-vertical hydrocarbon microseepage is the routine measurement by geochemists of anomalous amounts of light hydrocarbons in soil gases and soils directly over petroleum deposits. Soil gas hydrocarbons have very similar carbon isotope ratios to the gases in the underlying deposits, while ratios for biogenic hydrocarbons differ from those values. This, along with the good compositional correlation between surface microseeping hydrocarbons and the type of underlying reservoir, is convincing evidence of vertical hydrocarbon migration (Saunders et al., 1991).

Gases moving vertically through the strata are controlled by at least three seepage mechanisms (Matthews, 1996): (i) effusion, as a free gas, thought to be the major factor leading to macroseeps. It is due principally to the very large pressure differential that exists across a petroleum reservoir; (ii) diffusion of gases usually dissolved in vertically migrating waters, that can be observed passing through seemingly impenetrable barriers such as metal and glass – this form of migration produces microseeps; (iii) vertical movement of low-molecular-weight hydrocarbons dissolved in water through capping shales as a result of hydrodynamic or chemical potential drive (Duchesner, 1980). Matthews concluded that the most reasonable hypothesis involves the vertical ascent of ultra-small (colloidal size) gas bubbles through a network of interconnected, groundwater-filled 'microfractures'. Buoyant colloidal gas bubbles are readily displaced upward at rates up to several millimetres per second. This fast ascent explains the rapid development of soil gas light-hydrocarbon anomalies over newly filled gas storage reservoirs, and the rapid disappearance of such anomalies after a reservoir is depleted. Usually microseeps are invisible and at such low levels that they cannot be distinguished without modern analytical methods.

Heavy (high molecular weight) hydrocarbons may migrate by processes such as water flushing (when dissolved in groundwater) or by squeezing from collapsing pore spaces as a result of compaction (Matthews, 1996).

An anomaly does not necessarily imply an economic petroleum accumulation and the explorationist must determine whether the seepage is just minor venting of petroleum. The present theories on microseepage support...
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The premise that a reservoir leaks even though it contains trapped hydrocarbons. The cross-sectional shape of the leaking pattern has conventionally been labelled a ‘chimney effect’ (Tedesco, 1995).

The near-surface expression of subsurface leakage may take various forms (Abrams, 1996): halo anomalies; fault-related anomalies; local trapping; and no anomaly. Halos have long been recognized in various parts of the world (Horvitz, 1985). These are ring-forming structures in which low concentrations of hydrocarbons occur in the sediments in the centre of the structure and high concentrations in the sediment above the edges. Some believe that these ring structures are associated with ‘chimneys’: near-vertical migration channels for oil and gas (Heggland et al. 2000). Faults act as natural pathways for the migration of oil and gas and many researchers (e.g., Voytov et al., 1972; Reitsema et al., 1978) have presented examples where hydrocarbon concentrations are greatest near faults. In many settings, localized subsurface barriers prevent migration of oil and gas to the surface. The hydrocarbons themselves cause methane sequestering in near-surface sediments by bacteria and form so-called gas hydrates: natural storages of gas-saturated sediment accumulations in the shallow subsurface (Kvenvolden, 1998). The perfect seals above these hydrates permit only marginal seepage to the surface. Lastly, many surveys have shown no detectable geochemical anomalies above subsurface hydrocarbon accumulations.

Microbial effects and hydrocarbon-induced surface manifestations

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 (1996) made a thorough review of the major hydrocarbon-induced changes affecting soils and sediments and their implications for surface exploration methods and applications. He believed that long-term leakage of hydrocarbons, either as macro- or microseeps, can set up near-surface oxidation–reduction zones that favour the development of a diverse array of chemical and mineralogical changes. The bacterial oxidation of light hydrocarbons directly or indirectly can 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 mobilization or immobilization of certain elements in the chimney, which thereby becomes mineralogically and chemically different from laterally equivalent rocks. The resulting alterations can include: the formation of calcite, pyrite, uraninite, elemental sulfur, and certain magnetic iron oxides; 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. Bleaching occurs whenever acidic, reducing fluids dissolve the ferric oxide (haematite) 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. 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. The problem in direct detection of microseeps via these alteration schemes is that it is difficult to separate background mineralogy from alteration mineralogy. The proposed alteration schemes by Saunders et al. (1999) are not clearly based on sedimentary or petrological environments, but they do provide a general classification that needs to be further refined.

Hydrocarbon-consuming bacteria and related organisms have been found in sediments, oilfield waters, and crude oil at depths up to 4200 m. Bacteria produce CO2 and organic acids in the process of oxidizing hydrocarbons. Additionally, sulphate-reducing species create H2S. Near-surface carbonate cements and carbonate build-ups on the sea floor have been attributed to CO2 generated by bacterial or chemical degradation of hydrocarbons seeping upward from petroleum.

Fig. 3 Reflectance spectra of solid CO2, CH4 and H2O (King and Clark, 1989).
Carbon dioxide produced by anaerobic bacterial degradation (or by oxidation) of hydrocarbons produces H$_2$CO$_3$, which in turn reacts with calcium silicates to produce secondary carbonate. Carbonate cement can also be generated directly from inorganic reduction of sulphates by:

$$\text{Ca}_3\text{Si}_2\text{O}_5 + 3\text{CaSO}_4 \rightarrow 3\text{CaCO}_3 + \text{CO}_2 + \text{H}_2\text{O} + 2\text{H}_2\text{S}.$$

(1)

Acidic solutions created by bacterial oxidation of vertically migrating hydrocarbons can leach potassium and possibly other radioactive elements from clays (mostly illite in soils). Low potassium anomalies have been found associated with microseeps.

Aeromagnetic anomalies with shallow-depth sources have been reported over oil and gas seeps. Hydrogen sulphide reacts with iron oxides (goethite) to produce magnetite; sometimes goethite is altered to magnetic forms of haematite. Microbial activity produces chemically reducing environments that precipitate uranium minerals. Several studies have identified the so-called edge leakage in soils on top of reservoirs. Carbonic acid dissolves calcium and iron and near-surface loss of CO$_2$ causes a reversal of the oxidation reaction and yields the precipitation of secondary calcium. The secondary calcium clogs the gas escape routes and gases deflect to the edges of the alteration zone.

**Detection of hydrocarbon-induced surface manifestations by remote sensing**

The remote sensing data most widely used in hydrocarbon exploration are aerial photography, radar, Landsat Multispectral Scanner (MSS), Landsat Thematic Mapper (TM), and airborne multispectral scanner data. Aerial photography has been used to map structures and stratigraphy since the 1930s. The use of side-looking radar images (SLAR) and synthetic aperture radar (SAR) subsequently provided enhanced the subtle expression of subsurface geological structures. Since the 1970s, with the launch of the Earth Resources Satellites, data for the Earth’s surface as observed from space have been obtained in a semi-operational way. MSS, SPOT and TM images have been used for ‘indirect oil detection’ (e.g. Lang et al., 1985a, b). The rapid development of remote sensing technology has also made it possible to carry out ‘direct detection’ of oil reservoirs by identifying the tonal anomaly that is the manifestation of hydrocarbon seepage. Remote sensing of hydrocarbon-induced alteration holds great promise as a rapid, cost-effective means of detecting anomalous diagenesis in surface soils, rocks and related vegetation. The most extensive studies were concerned with the reduction of ferric iron (red bed bleaching), the conversion of mixed-layer clays and feldspars to kaolinite, the increase of carbonate content, and the anomalous spectral reflectance of vegetation.

**Bleached red beds**

Bleaching of red beds occurs whenever acidic or reducing fluids are present to remove ferric oxide (haematite). Such conditions also favour the formation of pyrite and siderite from the iron released during the dissolution of haematite. The possible reducing agents responsible for bleaching red beds above petroleum accumulations include hydrocarbons and H$_2$S (Schumacher, 1996), while CO$_2$ may cause alteration.

Donovan (1974) reported that the colour of the Permian Rush Springs formation grades from reddish-brown for unaltered sandstone adjacent to the field to pink, yellow, and white along the flanks of the Cement anticline, and white along the flanks of the anticlinal axis, where maximum bleaching and iron loss occur in the Cement field area of Oklahoma. In the Sheep Mountain anticline, Bighorn Basin, WY, Landsat TM data isolated areas of red-bed bleaching within the Chugwater Formation that correspond spatially to known hydrocarbon deposits. Bleached areas were quantified spectrally by a decrease in the band 3/1 ratio in conjunction with an increase in total reflected radiance. The potential of this technique is greatest in areas of sparse vegetation and susceptible clays and red beds.

The geology and geochemical alteration associated with Lisbon Valley field in southeastern Utah have been described in considerable detail by Segel et al. (1986). They report that the distribution of the bleached outcrops of the Triassic Wingate formation approaches the geographical limits of the oil and gas reservoirs at depth. A ratio of TM bands 2 and 3 was used to delineate variations in ferric-iron content. Ferric-iron rich exposures exhibit very low 2/3 ratio values, while ferric-iron poor rocks have relatively high 2/3 ration values. Density slicing was used to delineate the bleached rocks (Segel and Merin, 1989). The ferric iron exhibits an absorption feature at 0.9 µm and the visible spectrum falls off sharply to the blue producing a maximum near 0.80 µm. Under ideal laboratory conditions, the ferrous iron in non-transparent minerals such as pyrite and magnetite shows a low total reflectance, while in transparent mineral such as siderite, it shows a broad shallow band at 1.0–1.1 µm. These characteristics can be used in remote sensing data processing for separating bleached from unbleached red beds.

**Clay mineral alteration**

The production of CO$_2$, H$_2$S and organic acids as a result of the microbial oxidation of hydrocarbons in near-surface soils and sediments can create reducing, slightly acidic conditions that promote the diagenetic weathering of feldspars to produce clays, and may lead to the conversion of normally stable illitic clays to kaolinite. Clays thus formed remain chemically stable unless their environment is changed (Schumacher, 1996).

In Utah’s Lisbon Valley field, Segel et al. (1986) report that bleached portions of the Wingate Sandstone directly overlying the field contain primarily kaolinite clays, whereas the unbleached areas of the sandstone located away from the field contain fresh plagioclase and muscovite. The bleached Wingate contains three to five times more kaolinite than the unbleached rock. Segel and Merin (1989) defined the variations in clay mineral content, which have been directly correlated with differences in the relative proportion of kaolinite, using a colour-coded TM 5/7 ratio. Kaolinite-rich rocks associated with bleached exposures that overlie the hydrocarbon accumulation at the Lisbon Field exhibit the highest 5/7 ratio values.

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Kaolinite exhibits a very strong absorption feature centred at 2.2 μm, as well as the presence of a diagnostic, subordinate, absorption feature (known as a doublet) centred at 2.16 μm. This can be indicative in clay mineral rich areas.

**Carbonates**

Diagenetic carbonates and carbonate cements are among the most common hydrocarbon-induced alterations associated with petroleum seepage. Pore-filling calcite and replacement calcite is most common. These near-surface diagenetic carbonates are formed principally as a byproduct of petroleum oxidation, and particularly of methane. Carbon dioxide evolves and reacts with water to produce bicarbonate; this bicarbonate bonds with calcium and magnesium in groundwater and precipitates as carbonate that has an isotopic signature matching that of the parent hydrocarbon(s) (Schumacher, 1996).

In the Palm Valley gas field, Amadeus Basin, central Australia, a distinct colour anomaly in sandstones was detected by digital image processing of NASA NS-001 aircraft thematic mapper simulator (TMS) scanner and Landsat Thematic Mapper (TM) data. Laboratory spectra of brown sandstone from within the colour anomaly, have only about half the brightness of the red sandstone, with a reflectance maxima of about 25% at 1850 nm. Laboratory spectra of calcere show a similar curve to the brown sandstone, but with increased brightness towards the visible wavelengths. In the calcere, a weak to moderate absorption feature at 2322 nm is caused by the carbonate (calcite) content, and weak absorption features at 2200 nm and 1411 nm suggest the presence of clays. Based on the field spectral reflectance, a distinctive colour discrimination can be obtained using calibrated TMS band-ratios.

In relatively arid regions such as West Texas, carbonates may be visible on aerial photos or satellite imagery as light tonal anomalies indicating an excessive development of calcite in the surface soils (Thompson et al., 1994). In the Junggar Basin in Xinjiang, China, a strong delta carbon anomaly with a major increase in total carbonate in soil was identified from Airborne Short-wave Infrared Split Spectral Scanner data. Four channels at the wavelength range of 1.550–1.650 μm, 1.985–2.085 μm, 2.037–2.137 μm, and 2.039–2.193 μm were used for anomaly extraction. The most common calcite bands are from 1.8 to 2.6 μm – at 1.8 μm, 2.0 μm, 2.16 μm, 2.35 μm, 2.55 μm – and can be used to map carbonate (calcite) concentration.

In summary, mineral alteration related to hydrocarbon microseepage can result in:

- creation of hydrogen sulphide due to bacterial activity;
- production of secondary (enrichment) in carbonate (calcite, siderite) in combination with CO₂ and H₂S production;
- low potassium anomalies in soils (illite);
- magnetic anomalies in which goethite is altered to magnetic forms of haematite;
- build up of uranium concentrations bleaching of red (haematite rich) sandstones;
- edge leakage (concentration of calcium around the edges of zones of microseepage) and secondary calcite enrichment.

**Geobotanical anomalies**

Geobotanical anomalies occur as a result 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 – with absorption at 0.66 and 0.68 μm for chlorophyll a and b, respectively – is the most important (Elvidge, 1990). Changes in the chlorophyll concentration produce spectral shifts of the ‘red-edge’ absorption near 0.7 μm (the point of maximum slope on the reflectance spectrum of vegetation between red and near-infrared wavelengths, defined as the wavelength of maximum ΔR/Δλ). This red-edge shifts towards the blue or red part of the spectrum with loss or increase of chlorophyll (Boochs et al., 1990). The results are:

(i) a decrease in the height of the infrared shoulder owing to structural damage; (ii) an increase in the reflectance at the chlorophyll absorption maximum owing to decreased leaf chlorophyll; and (iii) a shift in the position of the red-edge towards shorter wavelengths.

Hydrocarbon microseepage creates a chemically reducing zone in the soil column at depths shallower than would be expected in the absence of seepage. Such leakage stimulates the activity of hydrocarbon-oxidizing bacteria, which decreases soil oxygen concentration while increasing the concentration of CO₂ and organic acids. These changes can affect pH and Eh in soils, which, in turn, affects the solubility of the trace elements and consequently their availability to plants (Schumacher, 1996). The environmental change will affect the root structure of vegetation, to ultimately influence the vigour and hence, spectral reflectance of those plants. As a prerequisite of the identification of vegetation anomalies by remote sensing, ‘normal’ plant variability has to be assessed by judging plant distribution, the presence of indicator plants, or morphological changes in plants induced by excesses or deficiencies in available soil nutrients. The remote sensing applications include:

- (i) research into the spectral characteristics of the anomalous or stress vegetation species caused by hydrocarbon microseepage and (ii) mapping anomalous or stressed vegetation species from imagery.

Bammel and Birnie (1994) conducted a geobotanical reflectance study at five areas in the Bighorn Basin, WY to determine whether the spectral response of sagebrush could be a useful tool in hydrocarbon exploration, with measurements collected in the visible and near infrared regions (0.45–1.1 μm). The study showed that the most effective indicator of hydrocarbon-induced stress in sagebrush plants is a consistent blue shift (to shorter wavelengths) of the red-edge. This shift can only be detected where the sagebrush is actually growing in large amounts of surface-visible occurrence or perhaps in areas of profuse (but not visible) vertical seepage. Spectral reflectance intensity data were found to have no significant correlation with the presence or absence of surface or subsurface hydrocarbons.

In the Stoney Point oil field, MI, USA, high-resolution Fluorescence Line Imager (FLI) data were collected in both spatial mode and spectral mode that cover the spectral range of 430–805 nm in 288 channels. The
stress-related changes found were: (i) a decrease in the height of the infrared shoulder (\(R_s\)) owing to structural damage; (ii) an increase in the reflectance at the chlorophyll absorption maximum (\(R_p\)) owing to decreased leaf chlorophyll; (iii) a shift in the position of the red-edge (\(\lambda_p\)) towards shorter wavelengths. A stress image where low digital numbers represent an anomaly was created by multiplying \(R_s\) by \(\lambda_p\). Encouraging relationships were found between C2–C4 soil hydrocarbons and anomalies in the \(R_s \times \lambda_p\) stress images.

High-resolution reflectance spectra of Douglas fir trees were measured at the Mist Gas Field, OR, using Arco’s IRIS spectroradiometer, built by Geo-physical Environmental Research, Inc. Results of the study indicate that Douglas fir trees growing in areas of gas production have a different spectral signature from trees growing off-field. Trees growing off-field have higher reflectivity in the 750 nm to 1250 nm spectral region, and an absorption feature at 1200 nm is much stronger in off-field trees. Microscopic examination of needles from on-field trees revealed the presence of stress effects at the cellular level. Chlorotic trees display higher reflectivity in the 550–650 nm region, and the sharp rise in reflectivity at 700 nm is shifted towards shorter wavelengths. The local presence of chlorosis is poorly correlated with commercial gas production. Trees characterized by both chlorosis and cell damage may be indicative of more severe stress conditions. The poor health of on-field trees may be caused by the presence of methane-induced geochemical changes in soil and groundwater above the gas reservoirs.

In the central portion of the Sao Francisco Basin in central Brazil, where natural gas seeps occur, eucalyptus plantation specimens in the anomalous area were poorly developed, showing clear signs of nutritional deficiency. The geochemical anomalies from the soil gas survey correspond with the biogeochemical anomalies. Spectral data were collected over anomalous and non-anomalous eucalyptus stands, using an airborne non-imaging sensor, named SADA (Airborne Data Acquisition System). The analysis of the data acquired by SADA and the corresponding TM band values show higher reflectance values in chlorophyll absorption band for the sites under hydrocarbon influence, compared to sites outside the anomalies. The presence of hydrocarbons seems also to produce a change in the internal structure of the canopy, which causes lower reflectance values at the reflectance shoulder (Banninger, 1990). In gas-affected areas, the spectral contribution from underlying soil energy is more evident as a consequence of lower vegetation density.

Over the Lost River gas field in the Appalachian Mountains, WV, the principal vegetation anomaly observed was the presence of maple trees over the gas field at sites where more typical oak–hickory climax vegetation would have been expected (Lang et al., 1985b). The results for the Lost River site show that the maple trees occur in an area of maximum hydrocarbon seepage (methane) and minimum soil oxygen content. The anomalous maple distribution may relate to anaerobic soil conditions that directly or indirectly influence the mycorrhizal fungi living on the trees’ root hairs, favouring maple trees whose fungi appear to be better able to tolerate the anaerobic soils than their counterparts living on the roots of oaks (Lang et al., 1985b). Aircraft NS-001 (The Aircraft Thematic Mapper Simulator) eight-band data were acquired during the investigation. The colour-composite image of visible green, red and near infrared is the best of all tried for species and species community discrimination.

At the Patrick Draw field, southwest WY, sagebrush is the predominant vegetation. The most pronounced anomaly observed here was an area of stunted sagebrush and an associated tonal anomaly visible on Landsat imagery. The anomaly overlies the field’s gas cap and occurs in a region of strong light-hydrocarbon microseepage (Richers et al., 1982, 1986; Lang et al., 1985a). The geology and production history of the field show that the sagebrush anomaly results from the upward migration of injected gases and waters used to maintain reservoir pressures in the field (Arp, 1992). These gases and waters produced anoxic, low-Eh (oxidation potential), high-pH, and high salinity soils that are toxic to the overlying sagebrush (Lang et al., 1985a; Arp, 1992).

NS-001 data were also used to map the vegetation density. The anomalous stunted sage is characterized by a decrease in vegetation cover of at least 10%. The simple Siegel and Goetz (1977) mixing model was used to separate the vegetation and soil/rock components for spectral analysis studies (Lang et al., 1985a). Multispectral video data with narrow bandwidth filters were used to evaluate their sensitivity when detecting environmental conditions associated with hydrocarbon microseepage at the Pollard oil field (Cwick et al., 1995). Correlation analysis revealed a statistically significant relationship between Mn concentrations and vegetation growth around actively producing well sites. Although single-band video data were generally not sensitive to biochemical variations, transformed video data exhibited several significant correlations with leaf Mn concentration, and the leaf Mn/Fe ratio. In particular, principal component 2 and the near-infrared/red ratio were sensitive to leaf Mn concentrations.

The spectral signatures of vegetation associated with hydrocarbon microseepage have been extensively studied. The green peak, the red trough, the position of the red-edge, and the height of the infrared shoulder are the main features to which attention should be paid, after considering that factors such as bedrock geology, soil type, slope, soil moisture, and climate can have a more pronounced effect than the presence of hydrocarbons (Klusman et al., 1992). (For applications of field and imaging spectrometry to the detection and mapping of hydrocarbon-related anomalies, also read Yang et al., 1999, 2000.)

Future trends

Trends in exploration

Exploration methods based on what are assumed to be hydrocarbon-induced soil and sediment alterations have long been popular, but the processes that produce the observed effects are not well documented. The nature and extent of the alteration can vary significantly not only laterally and vertically, but also temporally. The cause of these altered soils and sediments may well be hydrocarbon related, but it is an indirect cause at
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best and may not be the most probable cause. Seemingly ‘significant’ alteration anomalies need to be evaluated carefully to determine whether or not they are related to hydrocarbon seepage. This requires answers to the following questions: Is the anomaly a function of geology or an artifact of culture? If it is a result of geology, is the observed alteration syngentic or authigenic? If it is authigenic, is the anomaly seep-related or of nonseep origin? If seep-related, does the anomaly result from an active hydrocarbon seep or a palaeoseep? Finally, if the anomaly at the surface is to be related to a drilling objective at depth, does the anomaly result from mainly vertical migration or does the migration path follow a more complex route? Considerable research is needed before we can understand the many factors affecting the formation of these anomalies in the near surface (Schumacher, 1996).

Visible, near-infrared, and short-wave-infrared wavelength regions fall into the atmospheric windows mostly used for remote sensing purposes. The visible and near-infrared region is sensible for monitoring vegetation change and the spectral features in the 2.2 μm region are particularly valuable because they are common to alteration minerals and allow discrimination from non-alteration minerals which provide features only as close as 2.4 μm. The laboratory and field spectra of the hydrocarbon-induced altered minerals and associated vegetation have been studied in detail, but the spectral resolution of MSS and TM is not sufficiently high for comparison with laboratory or field spectra. The broad bandwidth cannot characterize all the absorption features caused by hydrocarbon microseepage, regardless of the type of enhancements employed or the type of information extraction method applied. In short, high spectral resolution imaging data are needed for the recognition of hydrocarbon-induced alteration and related vegetation changes (Yang et al., 2000). Remote sensing of hydrocarbon microseepage holds great promise as a method with which to recognize marginal and low-relief, structural prospects and all stratigraphic traps that are not detected by reflection seismic surveys. With better understanding of hydrocarbon microseepage and its surface manifestations and with higher spatial and spectral resolution imaging data, there is a better chance of delineating the surface anomalies associated with subsurface hydrocarbon reservoirs.

Trends in monitoring natural petroleum emissions

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).

Natural petroleum leakage is a poorly understood potential natural source of methane emission that affects the global greenhouse gas production. A recent example of a natural emission of thermogenic gas through deep reaching faults is presented from the Münsterland area, Germany, where up to 8 g m⁻² d⁻¹ of methane emanates into the atmosphere (Cramer et al., 2000a). Levels of methane in the water above the mud volcanoes and seeps for the Amsterdam mud volcano in the Anaximander Mountains along the Mediterranean Ridge vary by up to 13.5 μL L⁻¹, with highest levels in areas where greater activity occurs or where recent eruptions are inferred (Woodside, 2000). Another estimate of gas emission related to natural petroleum seepage comes from the south Caspian basin. Here, oil mud volcanoes occur that reach heights of 500 m with diameters of several kilometres. Mud volcanic eruptions are often accompanied by a flame reaching 200–300 m in height measuring 50 m around the base. The burning flame is can usually be observed from distances of 100–150 km. The volume of gas ejected into the atmosphere during such an eruption is estimated at 2 × 10⁻¹⁵ to 5 × 10⁻⁸ m³ (Guliev et al., 2000a). During the quiet period their emanation is 2–3 times less, amounting to magnitudes of 1.5–4 × 10⁻⁸ m³ of gas per day (Guliev et al., 2000a). A total yearly estimate of methane emanated from seeps in the south Caspian basin is 3 × 10⁸ m³ of methane (Cooper, 2000a).

Hence, methods that can aid in the quantification of the fluxes of hydrocarbons from natural petroleum leakage are needed. Remote sensing of the Earth’s surface may be such a method as shall be illustrated in the following sections.

An integrated geoscience approach for hyperspectral carbon microseepage detection

In the remainder of this paper, a case study is described that used high spectral resolution imaging data for petroleum prospecting in the Santa Barbara basin of southern California.

Data subsetting: vegetated and bare rock subset

The methodology used herein for the analysis of hyperspectral data for the detection of microseepage is outlined in Fig. 4. The hyperspectral data cube is first split into a vegetated and non-vegetated (soil/rock) subset by applying a Normalized Difference Vegetation Index (NDVI) threshold. The two subsets are analysed individually. Vegetation indices are quantitative measurements, based on digital values, which attempt to measure biomass or vegetative vigour. For living vegetation, a band-ratio strategy can be especially effective because of the inverse relationship between vegetation brightness in the red and infrared region. The absorption of red light (R) by chlorophyll, and the strong reflection of infrared (IR) radiation by mesophyll tissue, ensures that the red and near infrared values will be quite different and that the infrared over red ratio (IR/R) will be high. Non-vegetated surfaces, including open water, man-made features, bare soil, and dead vegetation parts, will not display the specific spectral response of vegetation, and the ratios will decrease in magnitude. Thus, the IR/R ratio can provide a measurement of the importance of vegetative reflectance within a given pixel.

The most popular and widely used vegetation index is the Normalized Difference Vegetation Index (NDVI) defined as

\[
\text{NDVI} = \frac{(\text{NIR} - \text{red})}{(\text{NIR} + \text{red})}
\]

(2)

Although commonly used, the NDVI has several drawbacks: it is influenced by the state of the atmosphere, illu-
mination and observation geometry and background reflectance of soils and rocks.

The non-vegetated soil and rock subset

For the non-vegetated subset, the aim is to map occurrences of calcite (enrichment) and the alteration of goethite to haematite. For this purpose three spectral matching approaches to the reflectance data are used: the spectral angle mapped (SAM), the cross correlogram spectral matching (CCSM; Van der Meer and Bakker, 1998) technique and spectral unmixing analysis (SMA; Settle and Drake, 1993). Target signatures for the end-members are derived from a spectral library of minerals resampled to the probe resolution.

Spectral Angle Mapping (Kruse et al., 1993) calculates the spectral similarity between a test reflectance spectrum and a reference reflectance spectrum assuming that the data are correctly calibrated to apparent reflectance with dark current and path radiance removed. The spectral similarity between the test (or pixel) spectrum, \( t \), and the reference (or laboratory) spectrum, \( r \), is expressed in terms of the average angle, \( \Theta \), between the two spectra as calculated for each channel, \( i \), as

\[
\Theta = \cos^{-1} \left( \frac{\sum_{i=1}^{n} r_i t_i}{\sqrt{\sum_{i=1}^{n} t_i^2} \sqrt{\sum_{i=1}^{n} r_i^2}} \right).
\]  

[3]

In this approach, the spectra are treated as vectors in a space with dimensionality equal to the number of bands, \( n \). The outcome of the spectra angle mapping for each pixel is an angular difference measured in radians ranging from zero to \( \pi/2 \) that gives a qualitative estimate of the presence of absorption features, which can be related to mineralogy.

The Cross Correlogram Spectral Matching algorithm (CCSM; Van der Meer and Bakker, 1998) matches unknown pixel spectra to known laboratory or field spectra by deriving statistics from single pixel correlogram functions. Reference spectra can be selected from a spectral library with the same spectral dimensions as the data cube or from the scene itself. A pixel cross correlogram is constructed by calculating the cross correlation coefficient between a test spectrum (a pixel spectrum) and a reference spectrum (a laboratory or pixel spectrum known to characterize a material of interest) at different match positions. By convention, the reference spectrum is moved, and negative match positions indicate a shift toward shorter wavelengths, while positive match positions indicate a shift towards longer wavelengths. The cross correlation is calculated as

\[
r_m = \frac{n \sum_{i=1}^{n} \lambda_i t_i - \sum_{i=1}^{n} \lambda_i \sum_{i=1}^{n} t_i}{\sqrt{n \sum_{i=1}^{n} \lambda_i^2 - (\sum_{i=1}^{n} \lambda_i)^2} \sqrt{n \sum_{i=1}^{n} t_i^2 - (\sum_{i=1}^{n} t_i)^2}}
\]  

[4]

where \( r_m \) is the cross correlation at match position \( m \), \( \lambda_i \) is the test spectrum, \( \lambda_i \) is the reference spectrum, \( n \) is the number of overlapping positions (spectral bands), and \( m \) the match position. The statistical significance of the cross-correlation coefficient can be assessed by a \( t \)-test.

Rather than aiming at representing the landscape in terms of a number of fixed classes, mixture modelling and spectral unmixing acknowledge the compositional nature of natural surfaces and strive at finding the relative or absolute fractions (or abundance) of a number of spectral components or end-members that together contribute to the observed reflectance of the image. Therefore, the outcome of such analysis is a new set of images that for each selected end-member portray the fraction of this class within the volume bound by the pixel. Mixture modelling is the forward process of deriving mixed signals from pure end-member spectra while spectral unmixing aims at doing the reverse, deriving the fractions of the pure end-members from the mixed pixel signal. A linear combination of spectral end-members is chosen to decompose the mixed reflectance spectrum of each pixel, \( R_i \), into fractions \( f_j \) of its end-members, \( R_{ej} \), by

\[
R_i = \sum_{j=1}^{n} f_j R_{ej} + \epsilon_i \quad \text{and} \quad 0 \leq \sum_{j=1}^{n} f_i \leq 1,
\]  

[5]

where \( R_i \) is the reflectance of the mixed spectrum in image band \( i \) for each pixel, \( f_j \) is the fraction of each end-member \( j \) calculated band by band, \( R_{ej} \) is the reflectance of the end-member spectrum \( j \) in band \( i \), \( i \) is the band number, \( j \) is each of the \( n \) image end-members and \( \epsilon_i \) is the
between the measured and modelled error, a unique solution is found from this equation by minimizing the residual error, $\varepsilon$, in a least-squares solution. This residual error is the difference between the measured and modelled DN in each band and should in theory be equal to the instrument noise if that only the selected endmembers are present in a pixel. Residuals over all bands for each pixel in the image can be averaged to give a root-mean-square (RMS) error, portrayed as an image, which is calculated from the difference of the modelled ($R_{mk}$) and measured ($R_{mp}$) pixel spectrum as

$$\text{RMS} = \frac{\sum_k \sqrt{\sum_i (R_{mk} - R_{mp})^2}}{m},$$

where $n$ is the number of spectral bands and $m$ is the number of pixels within the image. The solution to the unmixing is found through standard matrix inversion such as the Gaussian elimination method. Boardman (1989), however, suggested the use of singular value decomposition of the end-member matrix which has the advantage that singular values can be used to evaluate the orthogonality of the selected endmembers. If all end-members are spectrally unique, all singular values are equal. For a degenerate set of end-members, all but one singular value will be zero.

**The vegetated subset**

The aim of the analysis of the vegetated subset is to detect any anomalously high or low wavelength for the red-edge position, indicative of abnormal chlorophyll production possibly resulting from microseepage. Two approaches were implemented for estimating the red edge position: the "linear method" of Guyot and Baret (1988) and the "Lagrangian method" of Dawson and Curran (1998). The method of Guyot and Baret (1988) calculates first the reflectance at the inflexion point ($R_{me}$)

$$R_{me} = (R_{670} + R_{780})/2,$$

next it derives the red edge wavelength ($\lambda_{re}$) by

$$\lambda_{re} = 700 + 40\left[\frac{(R_{700} - R_{700})}{(R_{740} - R_{700})}\right],$$

where $R_{670}$, $R_{700}$, $R_{740}$ and $R_{780}$ are the reflectance values at 670, 700, 740 and 780 nm wavelength, respectively. Dawson & Curran's technique for estimating the red edge is based on a three-point Lagrangian interpolation. By definition, the value of the 1st derivative of the reflectance red edge at any wavelength $\lambda$ will be $d_\lambda$. The Lagrangian interpolation technique takes on a form

$$d_\lambda = a^\dagger d_{\lambda(l)} + b^\dagger d_{\lambda(l-1)} + c^\dagger d_{\lambda(l+1)},$$

where $d_{\lambda(l)}$, $d_{\lambda(l-1)}$ and $d_{\lambda(l+1)}$ are the 1st derivative values and $a$, $b$ and $c$ are constants derived from the wavelength positions of the bands $\lambda_{l}$, $\lambda_{l+1}$ and $\lambda_{l+2}$, representing the two bands on either side of the maximum derivative.

**Statistical data integration (SDI)**

The analysis of the hyperspectral data yields the following data layers: spectral angle (from SAM), probability (from CCSM) and fractional abundance (from SMA) of calcite, goethite and haematite, red-edge position from microseepage. Two approaches were implemented for estimating the red edge position. The basic proposition being tested is the presence or absence of a seep, formulated as

$$F_p \sim \text{'p contains an undiscovered seep'}. $$

The mathematical framework of the Bayesian implementation of the SDI is embedded in the work of Chung and Fabbri (1993). Consider a probability at any $A$, $\text{prob}(F_p)$, for the proposition $F_p$. This prior probability, that pixel $p$ will contain a future reservoir, is obtained by

$$\text{prob}(F_p) = \text{size of F/size of A.}$$

where $F$ denotes the unknown areas which will be reservoirs within $A$ (and ‘size of $B$’ would represent the size of the surface area covered by any subarea $B$ in $A$). $\text{prob}(F_p)$ has the same value for all $p$. The purpose of the modelling is to see how the probability at $p$ will be changed as the $m$ pixel values at $p$ are observed. At pixel $p$, the pixel value $v(p)$ of the $1^{st}$ layer is $c_1$ which is one of the $n_l$ classes (map units), $\{1, 2, n_l\}$. Consider a set of all pixels whose value in the first layer is $c_1$. The set is the thematic class in the first layer whose pixel value is $c_1$. The set is denoted by $A_{1c_1}$ and it is one of the non-overlapping $n_l$ subareas $\{A_{1c_1}, A_{1c_2}, A_{1c_m}\}$ in the $1^{st}$ layer. Assume that the occurrences at each pixel $p$ can be expressed as the joint conditional probability $\text{prob}(F_p|c_1, c_2, ..., c_m)$ that $p$ will be a future undiscovered oil/gas reservoir, assuming that the $p$ contains the $m$ values $\{c_1, c_2, ..., c_m\}$. When $\text{prob}(F_p|c_1, c_2, ..., c_m)$ is approximately similar to $\text{prob}(F_p)$, it can be stated that the pixel values at the $p(c_1, c_2, ..., c_m)$ do not add any useful information about whether the pixel is a undiscovered reservoir. Using the Bayesian rules

$$\text{prob}(F_p|c_1, c_2, ..., c_m) = \frac{\text{prob}(F_p) \text{prob}(c_1, c_2, ..., c_m|F_p)}{\text{prob}(c_1, c_2, ..., c_m)}$$

thus providing a reference for the conditional probability.

When it is assumed that $c_1$ will contain an undiscovered oil/gas reservoir and that the $c_1$,...,$c_m$ are conditionally independent given the condition $F_p$ ($p$ will contain an undiscovered oil/gas reservoir), this can be expressed as

$$\text{prob}(c_1, c_2, ..., c_m|F_p) = \text{prob}(c_1|F_p) \times \text{prob}(c_2|F_p) \times ... \times \text{prob}(c_m|F_p),$$

where the individual $c_i$ in the right-hand side should be read as ‘an event that the pixel $p$ has the pixvalue, $c_i$ in the $i^{th}$ layer’. Under the conditional independence assumption, the joint conditional probability becomes
Applying SDI: the Ventura basin (CA)

The study area is located in the Ventura basin near the cities of Ventura and Santa Barbara in southern California (USA; Fig. 5).

Probe data

The present study used airborne hyperspectral remote sensing data from the Probe-1 instrument (Fig. 6). Probe-1 is an airborne whiskbroom remote sensing device that collects data in the reflected solar region of the electromagnetic spectrum (0.4–2.5 μm). The data used covered the VIS-SWIR region in 128 bands with 15–16 nm band width and 16 nm sampling in the VIS, 12–14.5 nm band width and 13 nm sampling in the NIR, 11–13 nm band with and 12 nm sampling in SWIR 1 (1400–1813 nm) and 15–18 nm band width and 16 nm sampling in SWIR 2 (1950–2543 nm). The probe-1 data

\[
\text{prob}\{F_p|c_1, c_2, \ldots, c_m\} = \frac{\text{prob}\{F_p\} \text{prob}\{c_1|F_p\} \text{prob}\{c_2|F_p\} \ldots \text{prob}\{c_m|F_p\}}{\text{prob}\{c_1, c_2, \ldots, c_m\}} \times \frac{\text{prob}\{c_1\} \ldots \text{prob}\{c_m\}}{\text{prob}\{c_1, \ldots, c_m\}} \frac{\text{prob}\{F_p|c_1\} \ldots \text{prob}\{F_p|c_m\}}{\text{prob}\{F_p\}} \frac{\text{prob}\{c_1\} \ldots \text{prob}\{c_m\}}{\text{prob}\{c_1, \ldots, c_m\}}.
\]

Fig. 5 Location of the southern Californian basins.

Fig. 6 Location of the probe flight-lines with a geologically interpreted Landsat 7 image as backdrop.
were atmospherically corrected to surface reflectance and geocoded.

The probe-1 data covers the northwestern margin of the Ventura basin which forms part of the larger southern Californian basin range (Figs 5 and 6).

Geology of the Southern Californian Basins

The Southern Californian Basins were formed as irregular pull-apart basins at a time of irregular rifting within the simple shear system of the San Andreas Transform Fault. They were initiated by rifting as a consequence of clockwise rotation of the crustal blocks about vertical axes from the early Miocene (about 22 Ma) followed by later thermal subsidence. In Fig. 7, a structural cross-section is given to position the Santa Barbara and Ventura basins in a regional geological context. Palaeomagnetic data have shown that 25% of the surface area of Southern California has undergone clockwise rotation of 90°.

Many authors have recognized that the Southern Californian Basins, including the Ventura basin, have experienced a late stage basement-dominated shortening in the latest Miocene to early Pliocene (6.5–5 Ma) after the initial extension in the early Miocene. Major anticlines were developed as fault bend folds and fault propagation folds. No major Pliocene or Quaternary strike-slip occurred in any of the faults. The major thrust faults merge with regional detachments beneath the transverse ranges and in the northern Peninsular ranges. The depth to the detachments is thought to be about 10–15 km.

Shortening in the Ventura basin is taken up mostly by E-W-trending reverse faults, blind thrusts and folds including the Santa Ynez and Lion Fault set in the north and the Oak Ridge Fault in the south (Figs 5 and 6). In the northwestern and northeastern parts the basin infill is overthrust by the N-dipping Red Mountain and San Cayetano faults. In the north central part both the basin and its infill material is back-thrusted over the older units along the Lion Fault set, forming a triangular zone in which the basin in-fill material is vertical to steeply dipping to the west.

Stratigraphy

The basement to the Ventura Basin is composed of Cretaceous to Eocene marine strata (Fig. 8). Palaeocene units are represented by the Juncal Formation, composed of very thick arkosic sandstones interbedded with thin dark grey shale. The Eocene strata are represented by the Matilija, Cozy Dell, and Coldwater formations. These formations are exposed outside the Ventura basin and are missing in the southern part of the Oak Ridge Fault. The Matilija Formation is composed of thick-bedded, tan to mottled light greenish-grey arkosic sandstone, micaceous siltstone and shale. The Cozy Dell Formation is composed of dark grey, argillaceous to silty micaceous shale alternating locally with tan arkosic sandstone. The Coldwater sandstone is composed of hard, tan, arkosic sandstone with intercalations of greenish grey siltstone and shale of marine origin.

The Oligocene Sespe Formation is composed of continental red beds characterized by maroon to red and locally green silty shale, interbedded red to pinkish-grey sandstone and pebble-cobble conglomerates. The Sespe Formation interfingers with the overlying late Oligocene to early Miocene Vaqueros Formation, a non-marine to nearshore marine, thin- to thick-bedded, biotitic sandstone. The lower part is dark grey to black sandy siltstone and mudstone. It is the oldest unit lying on the continental Sespe Formation and indicates the onset of transgressive into the region in early Miocene. The Sespe and Vaqueros Formations constitute the lowermost competent units above which the main detachment horizons were developed (Fig. 8). The Rincon Formation (early Miocene) is composed of poorly bedded grey shale and siltstone. It is the least competent layer within the Ventura Basin and forms the core of the Sulphur Mountain Anticlinorium, implying ductile deformation within the formation. The Monterey Formation is composed of contorted siliceous shale grading upwards into punky, diatomaceous silt, laminated diatomaceous siltstone and diatomaceous mudstone.

Fig. 7 A regional simplified cross-section across the transverse ranges of Southern California showing the structural position of the investigated Ventura basin. Legend: 1, Cretaceous strata and Franciscan assemblage (unnamed); 2, Eocene strata (Juncal up to Goldwater formations); 3, Oligocene strata (Sespe and Vaqueros Fm.); 4, Miocene strata (Rincon up to Sisquoc formations); 5, Pliocene strata (Fernando formation); 6, Quaternary strata (Mudpit and Saugus formations); 7, Mesozoic ophiolites; 8, Mesozoic tonolite and mafic gneiss; 9, Mesozoic granite (formation names refer to Fig. 8).
ite and mudstone. The Sisquoc shale is composed of light grey shale, claystone, locally slightly siliceous and diatomaceous. The Repetto Formation is composed of silty sandstone, siltstone and claystone at the bottom (Repettian stage) and sandstone, pebbly sandstone and pebbly conglomerate at the top (Venturian stage). It is partly correlated with the Pico Formation of Pliocene age. The Mudpit and Saugus formations are composed of non-marine weakly consolidated silt, sand and cobble–gravel conglomerates.

Petroleum geology

It is thought that the primary source rocks in the region is the organic-rich rock of the Monterey units (i.e. Rincon and Sisquoc formations). TOC values can reach 18%, dominated by sapropelic material with an excellent capacity for generating liquid upon maturity. The distribution of carrier beds, potential reservoirs and seals is controlled partly by the style of basin formation and partly by broader, regional palaeogeographic considerations. Migration pathways and reservoirs in the Ventura basin are dominated by Miocene and Pliocene turbidites and associated deep marine sediments. Because of rapid syn-extensional subsidence in a narrow pull-apart basin, large volumes of sand and gravel have been deposited within the Ventura basin during the Miocene and Pliocene, forming extensive reservoirs. The presence of oil in the Pliocene units in the East Ventura Basin indicates that oil has migrated across the stratigraphic boundaries. Seeps occur only along the vertically dipping strata where the younger units back-thrust over the older units.

Results of SDI

The Probe-1 flight line used in this paper is shown in Fig. 9. The analysis was applied to the entire Probe-1 dataset, but for the purpose of illustrating the results the discussion is restricted to a spatial subset confined to known seeps over a site locally referred to as the Sulphur Mountain test site. The probe data was subdivided into vegetated and non-vegetated subsets. The non-vegetated area was analysed for calcite, goethite and haematite. The endmember spectra for these minerals were extracted from the probe spectral library. The analysis was restricted to the 2300–2400 nm range for calcite and to the 400–1000 nm range for the iron-bearing minerals. On the individual SAM images clear distinctions can be seen between the mineral species, which become even clearer when extracting profiles over known seeps in the Sulphur Mountain test site (Fig. 10). The example goethite SAM profile in Fig. 10 shows the decrease in goethite (note that high values of radians imply less similarity between known and
unknown spectra in the definition of the SAM) between pixels 100–110. A major seep area is located between pixels 90 and 100 and smaller seeps occur between pixels 75–90. The goethite SAM profile shows an edge-leakage effect demonstrated by a decrease in radian values from pixels 100 to 110. Hence, the anomaly is not located directly over the seep, but instead, some distance away from it. The vegetation anomaly, however, occurs vertically over the seep area.

The cross correlogram spectral matching algorithm was also applied to the subset using the same input spectra. The results confirmed the findings of SAM. Fractional abundances for the three minerals were also calculated using the unconstrained SMA (spectral unmixing) approach. The three minerals were included in the mixing and a vegetation spectrum as well, because vegetation seemed to dominate part of the scene. The profile for the fractional abundance estimates over the known seep for endmembers goethite, haematite and calcite reveals a decrease in calcite from pixels 98 to 120. Also note that the haematite and goethite endmembers seem to deviate in the pixels 70–90 range, whereas around the 90–120 range they show a similar pattern. The absolute values of the fractions are meaningless as the unconstrained version of the unmixing was applied. The reader should focus on the relative differences in the observed patterns.

The resulting images for the REP according to the linear and Lagrangian method appear to differ both in size as well as in pattern of the REP. Two profiles for the linear and Lagrangian REP were calculated (Fig. 10). These highlight the seeps that occur on the profile line as anomalous high wavelength positions of the red-edge. Both methods give the same position, although the Lagrangian method smoothes the signal and produces higher REP wavelength values because of the effect of the interpolation.

The results of the mineral mapping using SAM, CCSM and SMA were integrated with the locations of the known seeps in the probabilistic model described earlier (the spatial data integration approach). The resulting predictor map for future (or undiscovered) seeps is shown in Fig. 11, together with the predictor map for the vegetation stress and an extract from the geological map showing the seep locations. The predicted probability map for the mineral alteration provides especially spectacular results.
The image clearly shows an elliptical pattern of high probability values around the actual seep location forming what appears to be a halo. In the centre of the halo, low values give the appearance of a clogged area similar to the resulting patterns described in edge-leakage. That the vegetation stress analysis in this area revealed less information results from the fact that few pure vegetation pixels are found and that large parts over the anomalous area are relatively devoid of vegetation (Fig. 11).

Conclusions

As oil and gas reservoirs leak, there are areas of the surface of the Earth where light and heavy hydrocarbons occur. The presence of microseeps (primarily gas seeps) has an effect on surface mineralogy, and also gives rise to anomalous vegetation spectral responses. Using hyperspectral imagery, such features can be mapped. An integrated approach toward seep mapping from hyperspectral imagery using statistical data integration (SDI) techniques allows various geoscience data layers to be integrated within a statistical framework to allow prediction of unknown seeps. The normalized difference vegetation index (NDVI) is used to generate data from vegetated and non-vegetated areas which are analysed separately. Mineral mapping techniques are applied to the non-vegetated areas while the red-edge position is used to highlight areas of vegetation stress. The results are integrated using a spatial data integration approach that builds on Bayesian

Fig. 10 Profiles over a known seep located between pixels 90–100 (with minor seeps occurring between positions 75 and 90). SAM profile for goethite (right) and REP (left).

Fig. 11 Results and interpretation. False colour image of probe bands 16, 9, 4 in RGB with seeps (A), SDI probability minerals with interpretation of the anomaly (B), SDI probability vegetation (C), geological map (D) and SDI probability minerals with annotation. All probability maps display $P > 0.8$. 
statistics. This model allows the objective combination of the results from hyperspectral datasets with known seep localities. The present study demonstrates: (i) that it is possible to identify anomalous spectral responses resulting from natural gas seeps; (ii) that this information can be effectively integrated in a statistical framework; and (iii) that a Bayesian approach allows us zones of known seeps to be delineated confidently.

The model presented herein has been extrapolated to the entire probe dataset and an attempt made to validate the results. Other geoscience datasets, such as surface geology and geochemistry and field spectroradiometer measurements, may also be integrated into the model. Notwithstanding this ongoing work, the importance of the work presented in this paper lies in the methodology and to a lesser extent in the local findings.

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