

## **Seepage-Induced Magnetic Anomalies Associated with Oil and Gas Fields: Onshore and Offshore Examples**

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The presence of magnetic anomalies over oil and gas fields has been noted for several decades, but it is only in recent years that the phenomenon has been critically examined. Studies of geologically and geographically diverse regions document that (1) authigenic magnetic

minerals occur in near-surface sediments over many petroleum accumulations, (2) this hydrocarbon-induced mineralization is detectable in high resolution, broad bandwidth magnetic data acquired at low altitude and with closely-spaced flight lines, and in ground magnetic surveys, (3) the magnetic susceptibility analysis of drill cuttings and near-surface sediments confirms the existence of the aeromagnetic anomalies, (4) sediments with anomalous magnetic susceptibility frequently contain ferromagnetic minerals such as greigite, maghemite, magnetite, and pyrrhotite, and (5) approximately 80% of oil and gas discoveries are associated with hydrocarbon-induced magnetic anomalies.

The association between hydrocarbon seepage and the formation of authigenic magnetic minerals in the near-surface has important applications in hydrocarbon exploration. Application of this methodology can quickly identify the areas or prospects with the greatest petroleum potential. Although the discovery of shallow sedimentary magnetic anomalies does not guarantee the discovery of hydrocarbon accumulations, it does identify areas requiring more detailed evaluation, thereby focusing attention and resources on a relatively small number of high potential sites. Proper integration of near-surface magnetic data with geologic and seismic data can improve exploration success and reduce development costs. This presentation will be illustrated with examples from North Africa and North America, including the deep-water Gulf of Mexico.

## **Empirical Observations from Global Surface and Subsurface Calibration Geochemical Database**

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A worldwide surface geochemistry (SG) calibration dataset with over 20,000 surface core and well locations from over 30 petroleum and non-petroleum bearing basins, both onshore and offshore areas, has been organized as part of an industry supported research project. The SG calibration dataset includes both published and proprietary surface geochemical survey data, regional (site specific) and prospect delineation (grid) surveys, and detailed hydrocarbon (gas and oil) molecular data from near-surface soil and sediment measurements and subsurface exploration tests.

The global SG calibration database demonstrates key problems with several surface geochemical methods currently undertaken by many commercial contractors. Most of the collection and analytical procedures provide hydrocarbon compositions significantly different than hydrocarbons collected in petroleum reservoirs. Several SG calibration surveys with positive petroleum indicators based on contractor interpretations were found to have no hydrocarbons at depth. These differences are in part related to analytical procedures used to extract light and high molecular weight hydrocarbons from surface soil and sediments. In addition, interpretations often confused background, transported, and reworked hydrocarbons with localized migrated hydrocarbons. Proper interpretation of near-surface geochemical data requires the recognition of many problems such as background versus anomalous, recent organic matter interference and sorption, transported or reworked hydrocarbons, bacterial alteration, mixing with hydrocarbons from multiple origins, laboratory or field contamination, and fractionation-partitioning effects. It is also very important to understand basin geology to properly use near-surface geochemical measurements as a predictive exploration and prospecting tool especially in areas of structurally complex geology and multiple fluid flow directions.

## **Leakage Conditions of Rock Salt: Solid Bitumen-Impregnated Rock Salt from the South Oman Salt Basin**

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One of the most effective seals in sedimentary basins is halite, because of its extremely low permeabilities, high capillary entry pressures and a ductile rheology under most geological conditions. Microstructural observations on hydrocarbon-impregnated salt cores from the Infra-Cambrian Ara Salt of the South Oman Salt Basin show that this salt once lost its seal capacity in geological evolution. Diapirs of the Ara Salt enclose several highly overpressured carbonate reservoirs (the intra-salt Ara "stringer" play). Microscopically, some of these salt cores reveal abundant intragranular microcracks and grain boundary cracks, filled with solid bitumen, which was formed by thermal cracking of oil. In addition, this salt shows widespread evidence for crystal plastic deformation as shown by subgrains. Using subgrain size piezometry, the calculated maximum past differential stress for the Ara Salt around the stringer reservoirs is 2 MPa. Laboratory experiments (Popp et al., 2001) have shown that under such low shear stresses, dilatancy of rock salt is only possible at near-zero effective stress - i.e., if the fluid pressure is lithostatic. This means that oil-impregnation could have only occurred, if the oil pressure in the stringers reached the capillary entry pressure in the pore throats of the Ara

Salt, causing a diffuse dilatancy in the salt. This pressure condition marks the ultimate sealing potential of halite in the deep subsurface, whereby halite increases its permeability by more than five orders of magnitude and becomes a leaky seal.

### **Active Seepage Detection, Identification and Correlation Using Geophysical and Geochemical Methods, Yampi Shelf, Australia**

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Two recent offshore surveys (GA S276 and AIMS SS06/2005) have been carried out over the Cornea oil and gas discovery. Plumes of gas were observed using side-scan sonar (100 & 500 kHz) rising up from reflective blocky features a few meters across and/or pockmarks up to 10 m across and ~1 m deep. Active seepage was found around areas of attenuated seismic signal or high velocity pull-up on 3D and 2D data, related, presumably, to secondary carbonate cementation. The plumes were also observed using hull-mounted echo sounders (12, 120, 200 kHz) and were most intense during low spring tides. A range of cemented tubes were sampled using dredges during both surveys. These ranged from clearly identifiable Sabelariid worm tubes to highly encrusted carbonate tubes that may be abiogenic. Analysis of highly encrusted tubes revealed a range of n-alkanes from C<sub>13</sub> to C<sub>32</sub>, maximising around C<sub>16</sub> with no odd over even preference.

In one area gas was seen at the surface, and bubbles broke with thin oily films. Moreover, oily globules were observed in the water column during sampling (SS06/2005). Gas bubbles were collected and analysed for molecular and isotopic composition, revealing a very dry gas (99% methane,  $\delta^{13}\text{C} = -41\text{‰}$ ). This composition is very similar to the gas analysed from the Cornea reservoir and indicates that seeping hydrocarbons are either derived from the reservoir or a similar hydrocarbon source. The location of this active seep area (0.5 x 1.4 km) has also shifted over 1 km between the two surveys.

### **Identifying False Positives in Synthetic Aperture Radar (SAR) Data Over the Southern Timor Sea, Northwest Australia: Implications for Remote Sensing and Acoustic Seepage Studies**

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A cost-effective method of screening offshore environments for potential indicators of hydrocarbon seepage, particularly in frontier regions, is through remote sensing and acoustic technologies. However, none of these tools in isolation are diagnostic of seepage, and as such, accurate identification of false positives within individual datasets is critical.

The Timor Sea region of the North West Shelf is one of natural hydrocarbon accumulation and seepage, and the current model for the spatial distribution of that seepage is partly based on Synthetic Aperture Radar (SAR). SAR identifies areas in which the capillary waves on the ocean surface have been damped, therefore it is a highly successful tool in delineating natural hydrocarbon seepage that forms oil slicks. However, damping of capillary waves may occur through a variety of alternative processes. Multibeam swath bathymetry and acoustic doppler current profile data indicates that tidal current flows may have contributed to the formation of slicks previously documented in the Timor Sea. Additionally, annular to crescent-shaped SAR slicks over carbonate reefs and shoals in the region that exhibit wind or wave driven 'feathering' are interpreted to be caused by a regional coral spawn event. Reinterpretation of these false positives may assist in accurately constraining the extent and frequency of active hydrocarbon (particularly oil) seepage in the region.

A similar process of judicious false positive screening is being applied to SAR over frontier exploration areas (in assessing potential seepage on the Central North West Shelf), and to archived echosounder data to differentiate between seepage and biological phenomena.

### **A Surface Geochemical Survey from Deepwater Offshore Brunei**

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Surface geochemical prospecting involves the search for near-surface or surface anomalies of hydrocarbons, which could indicate the occurrence of petroleum accumulations or active source rocks in the sub-surface. The methodology, as applied in offshore basins, covers a range of techniques, from observation of visible oil seepage at the surface to detection of micro-seeps in near surface sediments using sensitive analytical techniques. The methodology for surface geochemical surveys is the subject of continuous development. The current, most favoured practice is to detect possible migration pathways from the deep to the near-surface with the aid of seismic data. The expression of such pathways at the surface is then sampled and analysed. The results of such a survey, in deep water offshore Brunei, are presented, together with conclusions based on the full suite of surface geochemistry analyses, together with details regarding sampling and preservation of the shallow core samples. The use of analyses of the different gas fractions is presented, together with comparisons of Total Scanning Fluorescence and gas chromatography (GC) and combined gas chromatography – mass spectrometry (GC-MS) of the extract. A number of hydrocarbons seeps were detected in the survey area, ranging from being light oil- to condensate-associated, with varying degrees of biodegradation, and including seeps where hydrates were observed in the shallow cores. From the variation in GC-MS data, the light oils are proposed to have been generated in a deltaic / terrestrial source rock similar to known Brunei oils, with the possibility of two facies / formation variations contributing in different parts of the area.

## **Spectral Detection of Oil and Gas Seeps on the Ocean Using Airborne and Satellite Sensors**

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Spectral signatures of gas and oil seeps have been identified by analysing airborne hyperspectral data (Hymap Sensor) acquired over areas of controlled oil release at floating production facilities and at sites of known natural gas seepage. These data support theoretical predictions that thin oil films do not exhibit characteristic spectral absorption lines in the near infrared region. Instead, the modification of water albedo in a broad spectral range provides two different signatures for oil and gas. These spectral signatures have now been applied to locate unknown oil and gas seeps using hyperspectral data acquired over selected targets on the North West Shelf of Australia. The location of these seeps is consistent with their geological setting.

The nature of the spectral signature has allowed the feasibility of multispectral data for seep detection to be tested. Multispectral images acquired on various satellite borne detectors were tested for natural hydrocarbon seep detection over Coal Point, California, an area of active hydrocarbon seepage. This approach has allowed practical limits for seep detection to be established based on resolution and signal-to-noise ratio for these sensors. More testing is needed to fully establish the limits of applicability of the multispectral approach. However, the methods presented here show promise for quick and cost-efficient screening of large areas of continental shelf for gas and oil seeps.

## **Development of Methods to Collect and Analyze Gasoline Range (C5 to C10) Hydrocarbons from Seabed Sediments**

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Gasoline range hydrocarbons (C5 to C10) are usually associated with petroleum generation. Up to present few surface geochemical surveys have attempted to evaluate gasoline range hydrocarbons in near-surface marine sediments. The key to sampling these light hydrocarbons in marine sediments is to capture and analyze them with minimum loss or fractionation using a solvent-less method. In this study, a Solid Phase MicroExtraction (SPME) method was tested for this purpose. SPME was initially developed for analyses of volatile aromatic hydrocarbons (BTEX) using fused silica fiber coated with PDMS (polydimethylsiloxane liquid) immersed to aqueous phase. Subsequent investigations showed that much better results were reached if the fiber was exposed to a headspace above the solution (HSPME - Headspace Solid Phase MicroExtraction).

The sediment seepage HSPME extraction method is based on the condition that phase/composition equilibrium is reached between sediment/saline water mix, disrupter headspace, and SPME fiber coated with sorbent. In our experiments, we evaluated the effectiveness of HSPME to detect and measure low concentrations of migrated crude oil in marine sediments. The following optimum laboratory procedure for HSPME gasoline monitoring was established: collect sample in sealed disrupter chamber, use water bath to keep stable laboratory temperature, NaCl saturated solution to help aromatic compound move out of the solution to vapor phase, and sufficient time to reach equilibrium. The results show that HSPME is very sensitive with detection limit of approximately 6 ppm. HSPME proved to be suitable to reveal the natural background and microseepage level of gasoline hydrocarbons in marine sediments.

## **Geochemical Exploration in Deserts: Strategies for Success**

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Desert environments are well suited for hydrocarbon microseepage surveys. Both soil gas and microbial methods are effective in deserts, however, we recommend avoiding areas with moving sand dunes. Hydrocarbon microseepage surveys in deserts require careful planning and implementation. Microseepage data are inherently noisy and require adequate sample density to distinguish between anomalous and background areas. To optimize the recognition of a seepage anomaly, the sampling pattern and sample density must reflect survey objectives, expected size and shape of the target, expected variation in surface measurements. Defining background values adequately is an essential part of anomaly recognition and delineation. Undersampling and/or the use of improper analytical techniques is a major cause of ambiguity and interpretation failures.

Results of microbial and soil gas surveys in the deserts of North Africa, the Middle East, and South Asia are presented here. These results illustrate the value of hydrocarbon microseepage data for high-grading basins, plays, and prospects. Reconnaissance surveys in Oman and Pakistan illustrate the value of such surveys to high-grade seismic leads and prospects, and identify areas that warrant further evaluation. Surveys in Algeria and Tunisia document hydrocarbon microseepage to the surface in spite of the presence of 200-400 meters of halite above Triassic reservoirs. Surveys in Yemen and Ethiopia survey illustrate the use of geochemical ground-truthing inferred seep-induced remote sensing anomalies. Results from surveys in Algeria, Egypt, Yemen, and Saudi Arabia successfully discriminated prospects on basis of hydrocarbon charge. Geochemical exploration surveys such as these are most effective when results are integrated with subsurface data.

## **New Methods for Data Processing in Geochemical Hydrocarbon Exploration and Their Application in Chinese Continent**

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One of the reasons why surface geochemical survey remains an unconventional approach is that there are many problems in data-processing, which cannot be solved by only using typical statistic methods. Most

anomalies processed with these traditional methods do not correlate with oil / gas fields in China. Since 1991, we have studied the methods for interference elimination and anomaly recognition to improve the application of the existing data. From the literature and geochemical data, two types of interference were revealed. One is the superimposition type originating mainly from microorganisms and contamination, and the other is the multiplication type resulting from variations in soil mineral components. Then a new method for eliminating both types of interference was established. Moreover, we found types of anomalies. One of them directly reflects oil and gas fields, referred to as micro-seepage anomalies. The other is related to faults, referred to as seepage anomalies. As the prospecting method varies with the anomalous types, they need to be recognized while separated from background. To do this, we established a set of methods employing statistics, multi-fractal model and back propagation artificial neural network. So far, the geochemical data from five provinces of China have been processed by using the new methods. The seepage anomalies, recognized after the interference elimination, display a string bead-shaped pattern and are distributed along faults. The micro-seepage anomalies are ring-shaped and coincide with oil / gas fields and traps. Reprocessing of existing geochemical data using the new methods can greatly improve geochemical hydrocarbon prospecting.

## **Diagenetic History of a Hydrocarbon-Bearing Large-Scale Sand Injectite (Santa Cruz, California)**

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Numerous large-scale bitumen-saturated sand injectite complexes occur in the Santa Cruz area (Central Coastal California). They were fed by the shallow-water coarse-grained deposits of the Santa Margarita Sandstones and are emplaced in the hemipelagites of the upper Miocene Santa Cruz Mudstones, a regional caprock. The reservoir-scale injectite complex which occurs at Yellow Bank Creek, ca. 10 Km north of Santa Cruz, consists of a dyke-sill complex a few hundreds of meters wide. It comprises resistant sandstones pervasively cemented by ferroan dolomite, which are intricately interfingered with limonite-stained sandstones. Bitumen traces are preserved in the dolomite cements.

Field observations and petrographic analyses were combined to investigate this complex arrangement of different cements with the purpose to understand the local diagenetic history and the general role of injectites in fluid migration. Catodoluminescence and scanning electronic microscopy reveal incipient dolomite corrosion of the cemented sandstones and common small residual dolomite crystals in the limonite-stained sandstones. The outcrop geometry of the cemented injectites is similar to those of limestone karst systems.

Hydrocarbon is therefore believed to have preferentially migrated along the permeable pathways supplied by the injectites in the caprock. Hydrocarbon oxidation and biodegradation supplied the dolomite which pervasively cemented the entire injectite complex. Following uplift of the area, subaerial weathering leached away and altered the Fe-dolomite into limonite staining. This study underscores the role of injectites in focusing basinal and meteoric fluid flows and the importance of the diagenetic history in controlling hydrocarbon migration.

## **Seepage and Leakage Next to Modern and Ancient Methane Clathrate Hydrate Accumulations: Comparative Sedimentology of the Pierre Shale Formation (Upper Cretaceous), Western Interior Foreland Basin of North America**

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In deep water modern seafloors, methane clathrate hydrates are common materials, as hydrate evolution is pressure and temperature dependent. Accompanying hydrate accumulation sites are zones of active, methane rich fluid expulsion that contain micro particles and dissolved solids. Organisms capable of exploiting methane and hydrogen sulfide from bacterial and inorganic anaerobic methane oxidation (AMO) thrive in these depositional environments. As a consequence of AMO, syndimentary seafloor diagenesis results in the precipitation of <sup>13</sup>C depleted carbonate minerals and the induration of the sediment with high and low magnesium calcite, ferroan calcite, aragonite, siderite and/or dolomite.

In the Pierre Shale Formation of South Central Colorado, limestones with vast numbers of coquinoïd nymhalucinid bivalves, abundant pellet grainstones, packstones and wackestones, and variably sized, mm to cm large, irregularly nodular, sparry masses occur in the Teepee Buttes. Significantly, the nymhalucinid bivalves belong to an extremely successful group of organisms that in modern settings exploits zones of AMO. Furthermore, nodular spar masses are displacive and consist of three phases of primary calcite cements: in order of precipitation these are high magnesium botryoidal fibrous, ferroan "dendrolublinite", and ferroan blocky. High magnesium botryoidal cements line the periphery of nodular spar masses and have  $\delta^{13}\text{C}_{\text{PDB}}$  ratios ranging from -44.8 to -46.3 ‰, reflecting a methanogenic source. Ferroan calcites display  $\delta^{13}\text{C}_{\text{PDB}}$  ratios with greater separation, ranging from -12.6 to -44.5 ‰, and are also found with cm to dm long tubules lined with ferroan calcite cemented terrigenous mudstone. Blocky ferroan spar with meniscate outlines seals the tubules. These combined features indicate that, during sedimentation of the Pierre Shale Formation, nodular methane hydrates precipitated in the sediment below the seafloor. In addition, nodular openings created following hydrate dissociation were stabilized with methanogenic carbonate mineral phases, and iron rich methanic fluids with micro particulates were expelled into overlying waters

## **Petroleum Seeps and Their Structural Control in North China Yellow Sea**

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Three hundred (300) seabed core samples were collected in the North China Yellow Sea to evaluate presence of petroleum charged structures. Sediment interstitial light and high molecular weight hydrocarbons were analyzed using headspace gas, TSF-aromatic, and K-V fingerprint analysis. Two major seepage areas have been identified, each with three seep sites: east and west seepage area.

The total gas concentration is less than 100ppm and wet gas fraction is less than 0.12(12%) in background of North China Yellow Sea. Total gas concentrations are from 786 to 1213 ppm and gas concentrations are between 0.20 and 0.26 in east seepage area, and from 622 to 893 ppm and gas concentrations are between 0.17 and 0.23 in west seepage area. The emissions maximum fluorescence intensity is from 374 to 1680 in east seepage area and 346 to 689 in west seepage area. The maximum fluorescence intensity excitation and emission wavelengths are from 228 to 232 nm and from 340 to 346 nm in east seepage area, and from 228 to 230 nm and from 340 to 343 nm in west seepage area. The K-V fingerprints show oil signature in east seepage area and gas signature in west seepage area. The basin of North China Yellow Sea consists of east depression, middle rise, west depression in structure. Each depression is composed of several structures. The structures control the near surface expression, not only for the seepage areas, but also for the individual seeps.