Annual Permit Report - EL 58/2008
2012

and

Report on available potential field and magnetic data and its applicability to hydrocarbon exploration in the Seymour region of Eastern Tasmania

E & P INVESTMENTS AUSTRALIA PTY LTD

INTRODUCTION

E & P Investments Australia Pty Ltd (E&P) made application for an exploration permit over an onshore area of Tasmania on November 25, 2008. The application was for a Category 4 Onshore Exploration Licence over an approximate area of 1560 sq km, located on the eastern coastline between Scamander and Cape Lodi.

E&P explained to the department that onshore hydrocarbon exploration in Tasmania to date has yielded little success. The Company's exploration approach was to conduct initial screening of the permit to ascertain evidence of surface hydrocarbons with a particular focus on oil, utilizing the Gore Surface Geochemistry sampling system. E&P believed it possible that hydrocarbon generation may have occurred offshore, east of the Tasmanian mainland in a hydrocarbon kitchen similar to the Gippsland basin, with migration to the coast and trapping in pinch-out or sub-cropping structures. The Company also considered the possibility of onshore hydrocarbon generation from the Gondwanan system and the Tasmanite oil shales.

Given the lack of success to date, E&P believed it fundamental that some evidence of possible trapped hydrocarbons is confirmed before the significant commitment to seismic acquisition and drilling is made. Providing the surface geochemistry confirms an economic zone of interest, a specific 2D seismic grid would be designed and acquired to cover the identified zone so that traditional geophysical interpretation and mapping can be conducted. The licence SEL 58/2008 was granted on July 3, 2009 by the Director of Mines and deemed to expire on 22 June, 2014.

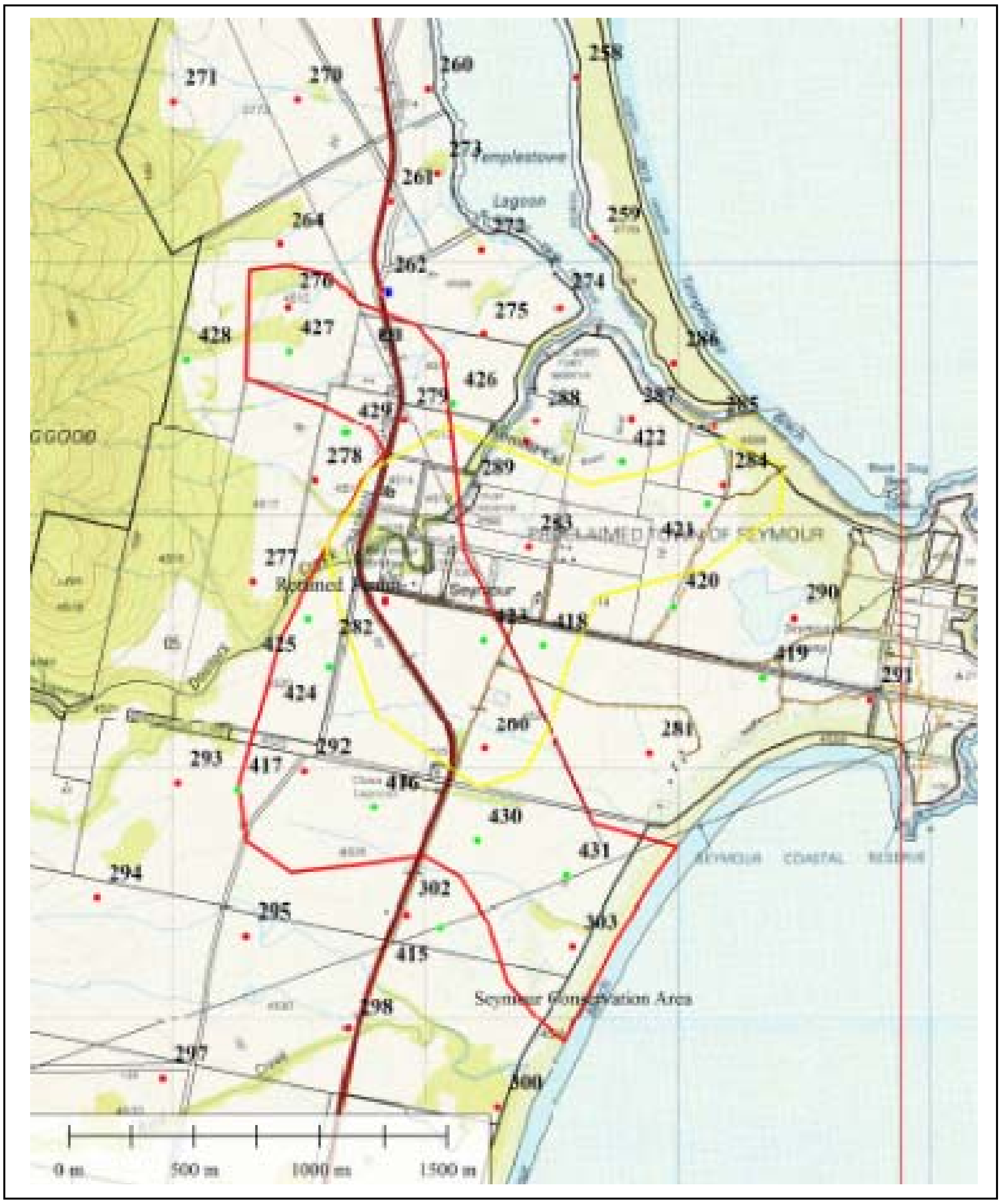
The Company has completed two Gore surveys and engaged independent consultants to assist in the planning and interpretation of the data, and has reviewed the commerciality of the only significant zone of interest to attempt to justify further commitment to exploration over EL 58/2008 (the Permit). To date, approximately $442,000 has been expended by E&P on the exploration and management of the Permit.

The Gore survey results were largely disappointing, with a few small zones identified from the results of the first survey. Most zones only provided a few positive sample results defining the closures, and the Company had concerns that some of the results possibly resulted from contamination. In particular, the positive sample points related to the zones near St Mary's were heavily discounted due to probable contamination given their proximity to built up areas and the extensive coal mining and transport operations.

Accordingly, a second Gore survey was conducted which specifically targeted three of the positive zones on the coast with a number of higher probability recordings so that a higher density grid of Gore infill samples could be installed, where greater care was taken to avoid existing infrastructure and roads.
The infill samples confirmed that the two northern zones were not valid. However, a small zone immediately to the west of Seymour remained valid and further geological assessment and economic screening was undertaken.

The Gore results are designed to demonstrate a surface signature of potentially trapped hydrocarbons where according to Gore the extent of the surface signature is considered likely to closely correlate to the sub-surface extent of the underlying trap. The Seymour zone was confirmed by both the initial and subsequent infill sampling and analysis. The zone lies in close proximity to a potential mapped fault derived from analysis of existing aero-magnetic data. It was calculated that the zone of interest had an estimated closure that may correlate to a potential trap of approximately 2 km2.

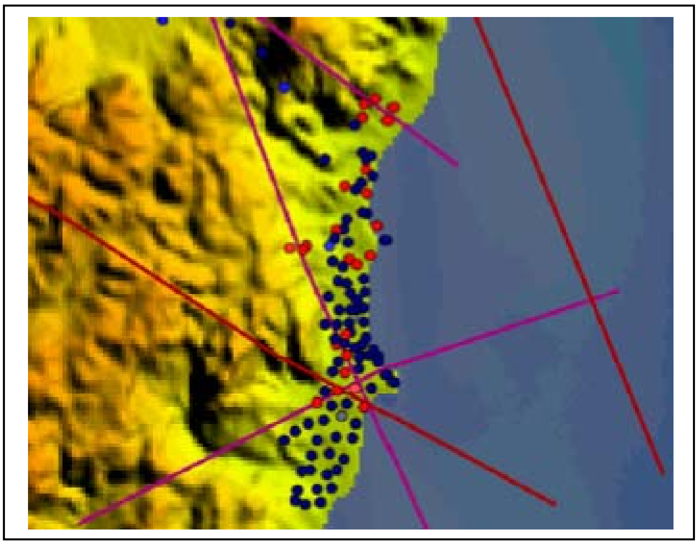
The following map shows the positive gore sample points and the possible areas of closure (red geochemical cluster analysis, yellow geochemical using Wombat gasfield (Victoria) calibration) in the Seymour area:



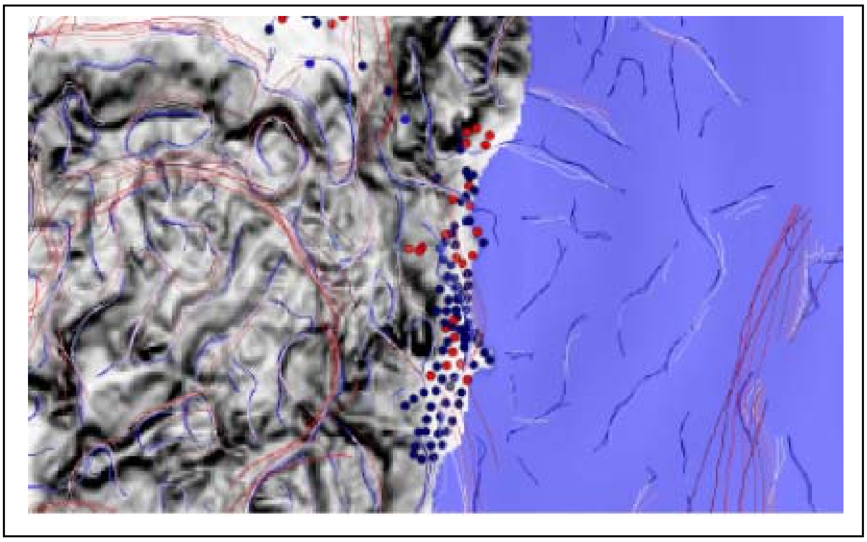
EXPLORATION ACTIVITY

Fault analysis:
Accordingly, most of the acreage (approximately 1112 square km) was relinquished and around 50 square km retained around the Seymour area for further investigation, where review and analysis of existing off-shore 2D seismic and aeromagnetic data will be undertaken to attempt to confirm fault sufficient off-set which may support the existence of an economic trap within the prospective zone identified by the Gore surface geochemistry.

The Company again engaged Drs O'Brien and Rawling to review the available seismic data in an attempt to confirm seismic evidence of various major faults identified from topographic and aeromagnetic data in the Seymour area.

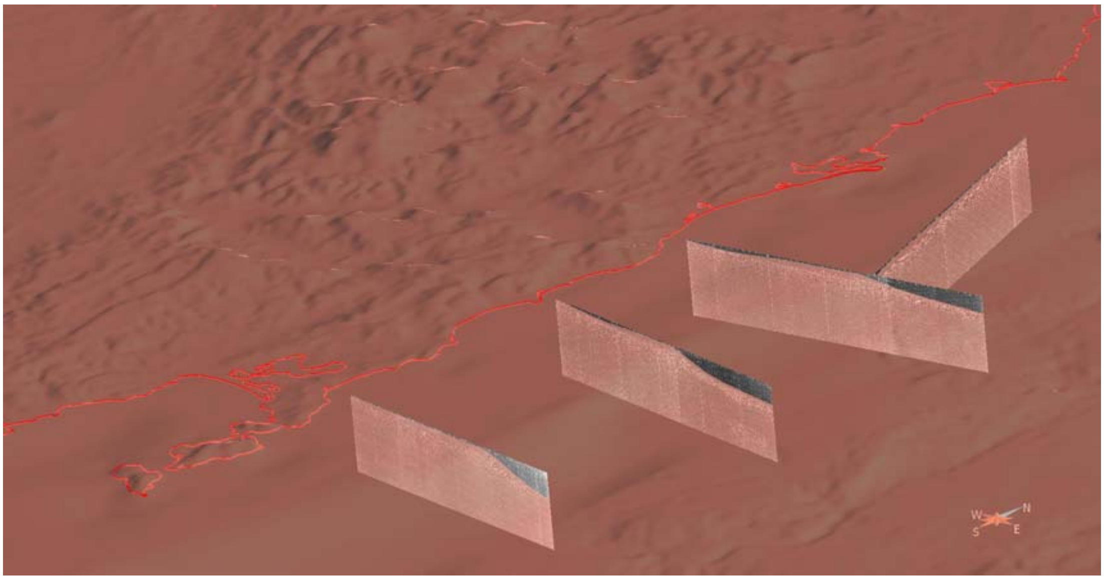


In order to better assess the geometry of the fault structure, a magnetic gradient edge (Worm) map was developed.



The worm data supports the suggestion that there is a strong structural control on the Gore sorber data and that this signature (at least in the region sampled in this study) is dominated by the effects of 2 fault sets oriented to the NNW and to the NW.

Seismic analysis:
Four off-shore 2D seismic lines were acquired in the 1969 by ESSO that lie adjacent to the permit area, T69B1, T69B2, T69B3 and T69B4. One, T69B2 comes within a kilometre of the Seymour region. Copies of the lines were acquired and digitized. Analysis of the available 2D seismic data was inconclusive, as no faults could be interpreted in the near shore zones to confirm the major faults identified by the previous topographic and aeromagnetic data analysis. Analysis of the 2D line could not support an argument for hydrocarbon migration from the deeper off-shore source rocks to the onshore zones of interest.



Magnetic anomalies analysis:
A number of authors have described a relationship between subtle magnetic anomalies and hydrocarbon producing structures (Wolleben & Greenlee 2002, LeSchack & Valasteen 2002, Berger et al 2002, Donovan et al 1979).

A number of papers have been published over the last 30 years describing a relationship between hydrocarbon reservoirs, seeps and magnetic anomalies. This effect has become known in some circles as the Donavan Effect due to its initial description by Donovan et al in 1974 and 1979. More recently workers such as Wolleben & Greenlee 2002, LeSchack & Valasteen 2002 and Berger et al 2002 have described workflows where this relationship has been used to constrain the extent of hidden hydrocarbon accumulations.

A further study was undertaken to assess the potential for applying similar techniques and workflows using existing datasets to in the study area to estimate offset on faults in the potential reservoir region.

Magnetic profiles were developed utilizing a grided magnetic image, which show a clear positive magnetic anomaly visible immediately to the west of the region of interest at Seymour. There is also a negative magnetic anomaly to the south and east of the high. Whist it could be argued that there appears to be a relationship between the magnetic low and some of the positive Gore samples, which could indicate fluid flushing and magnetite dissolution along a fault, this relationship is far from clear and is the opposite to that expected by the Donovan effect where fluids deposit magnetite resulting in localized and broad positive anomalies. Analysis of geological mapping data and more regional onshore RTP images (reduced to pole) indicate that magnetic high is likely to be associated with Jurassic dolerite exposures and that the medium wavelength stippling that produces the high and low anomalies is typical of these dolerites in NE Tasmania.

Summary

The available magnetic line data was not considered a high enough resolution to allow micro-magnetic analysis of the type proposed by Wolleben & Greenlee 2002 or Donovan et al 1979. There are no observable magnetic anomalies that can be attributed either to the faults in the target region or to fluid or hydrocarbon migration along these faults, which may suggest the absence or failure of a trapped reservoir.

E&P elected to undertake one final study using an independent geophysical firm, 3D-GEO Pty Ltd, experienced in the region with strong experience in geological modeling and working in regions with limited data, to see if any approach has been overlooked before making a final decision to relinquish the remaining acreage.

The micro-magnetic analysis report and supporting data/papers are attached to this Annual Report.

Report on available potential field data and its applicability to hydrocarbon exploration in the Seymour region of Eastern Tasmania

Dr Tim Rawling

Background

Two Gore surveys in the Seymour region of eastern Tasmania consistently defined a potential anomaly indicating the presence of surface hydrocarbons. The location of this anomaly coincides with the possible intersection of several faults interpreted from both potential field studies and analysis of other available remotely sensed datasets and high-resolution digital terrain models.

A number of authors have described a relationship between subtle magnetic anomalies and hydrocarbon producing structures (Wolleben & Greenlee 2002, LeSchack & Valasteen 2002, Berger et al 2002, Donovan et al 1979). The aim of this study is to assess the potential for applying similar techniques and workflows using existing datasets to in the study area.

Additionally profiles from the available gravity datasets would be used if possible to estimate offset on faults in the potential reservoir region.

Available datasets

A number of aeromagnetic and gravity datasets are available from the region of interest in eastern Tasmania. Numerous high resolution airborne surveys were conducted in the Finigal region for minerals exploration. Unfortunately there surveys do not extend far enough south to be of use in this study.

As a result the highest resolution magnetic data available was a combination of the 2007 (onshore) MRTAS_North_East_Tasmania_magnetic_line_data with a 200m line spacing and the 1994 (mostly offshore) Tasmania_Offshore_Tas_magwith a 400m line spacing. Primary flight-line data was downloaded from the GADDS website at GA and loaded for profile analysis and gridding.

The gravity data used in the study was a combination of land and ship based data of varying resolution complied in the National_Gravity_Database_AAGD07

Application of micromagnetic data to hydrocarbon exploration

A number of papers have been published over the last 30 years describing a relationship between hydrocarbon reservoirs, seeps and magnetic anomalies. This effect has become known in some circles as the Donavan Effect due to its initial description by Donovan et al in 1974 and 1979. More recently workers such as Wolleben & Greenlee 2002, LeSchack & Valasteen 2002 and Berger et al 2002 have described workflows where this relationship has been used to constrain the extent of hidden hydrocarbon accumulations.

In order to use these techniques successfully it is suggested that High-resolution aeromagnetic data (HRAM) is used and integrated with other remotely sensed datasets such as RADARSAT-1 imagery to first define the architectural elements that may be critical to trap formation (faults and structures)(eg Berger et al 2002).

In order to then use the data to constrain magnetic anomalies associated with the structures magnetic data flown at 100m or less and sampled every 0.1sec is required. The line data is then processed so that long , medium and short wavelength anomalies are defined. The data is analyzed and deviations from the expected background (long wavelength) profile are highlighted. When these deviations gradually increase and then decrease over a length scale similar to that expected of target reservoirs in the region they are highlighted. Analysis of imagery, geology data and cultural data is then used to look for possible causes for these deviations. When no other cause can be ascertained the anomaly is attributed to hydrocarbon leakage and other tests are run to verify this (chemical/seismic/etc).

The description provided by Wolleben and Greenlee 2002 is perhaps the most comprehensive (see accompanying documentation) and their Figures 1-4 highlight the nature of the expected anomalies.

Magnetic profiles across Seymour

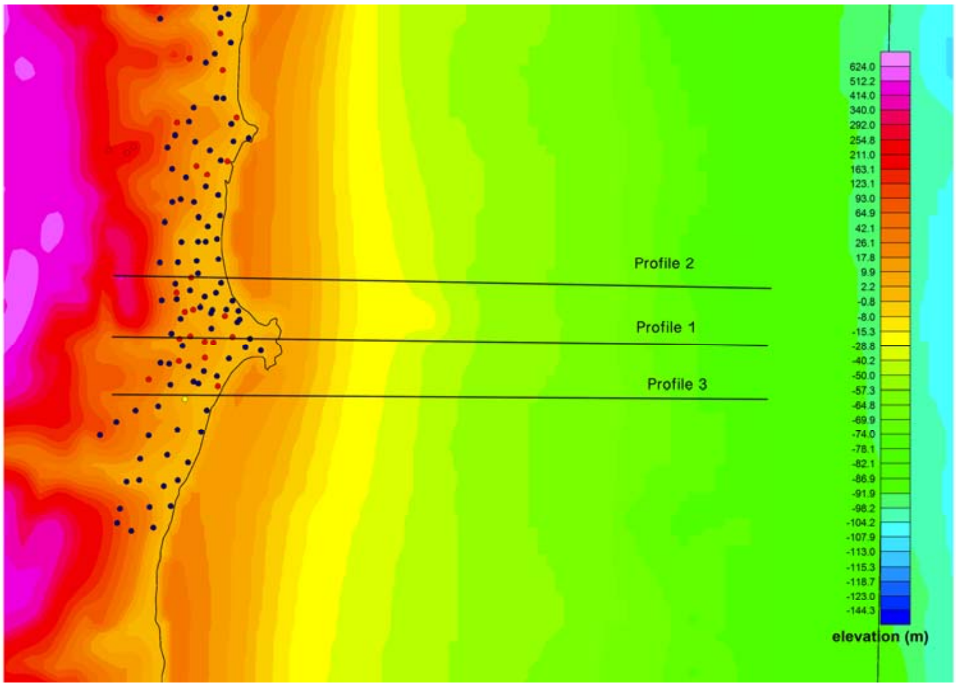
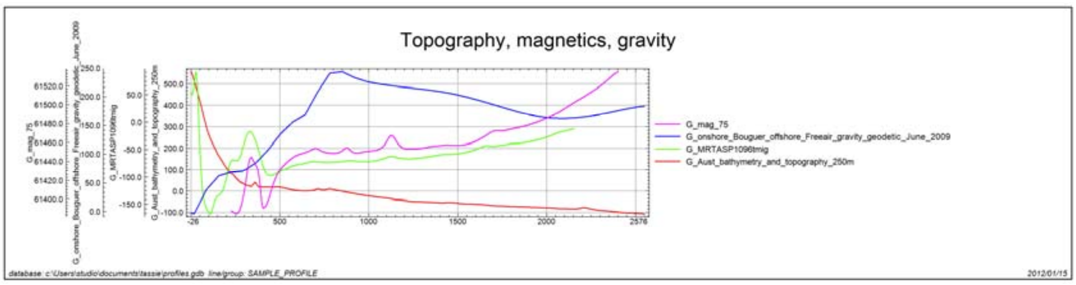


Figure 1 - Location map showing Profiles 1, 2 and 3 below.



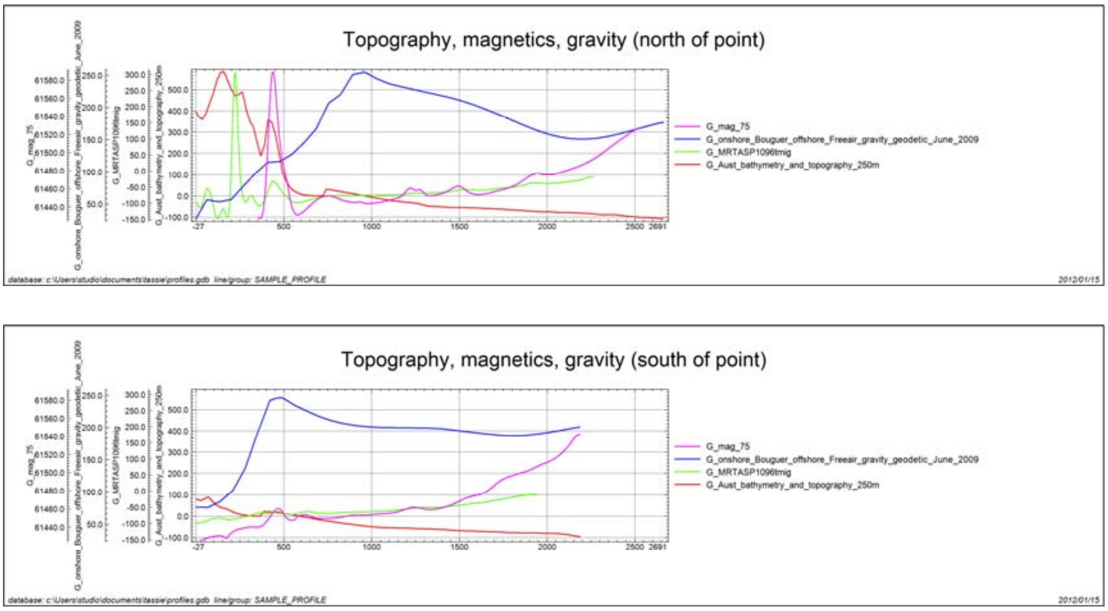


Figure 2 - Profiles 1, 2 & 3 showing topography, magnetics (regional and offshore lines) and gravity

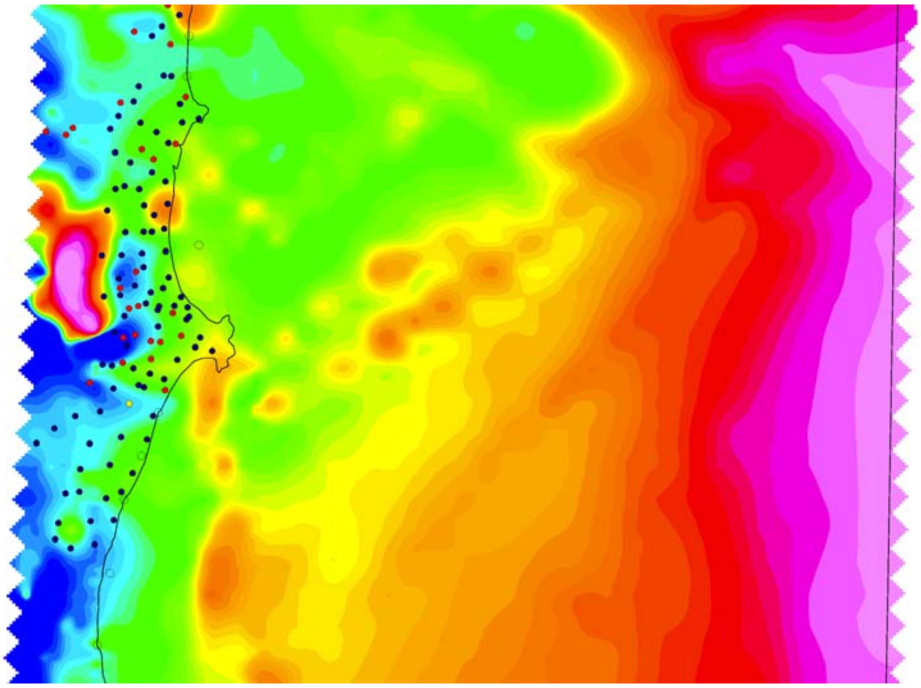


Figure 3 - 200m offshore magnetics data stitched with onshore data at coast. This is regrided data from original flight-line data downloaded from GADDS.

Analysis of the profiles presented above along with the grided magnetic image presented in Figure 3 show that there is a clear positive magnetic anomaly visible immediately to the west of the region of interest at Seymour. There is also a negative magnetic anomaly to the south and east of the high.

Whist it could be argued that there appears to be a relationship between the magnetic low and some of the positive Gore samples, which could indicate fluid flushing and magnetite dissolution along a fault, this relationship is far from clear and is the opposite to that expected by the Donovan effect where fluids deposit magnetite resulting in localized and broad positive anomalies. Analysis of geological mapping data and more regional onshore RTP images (reduced to pole) indicate that magnetic high is likely to be associated with Jurassic dolerite exposures and that the medium wavelength stippling that produces the high and low anomalies is typical of these dolerites in NE Tasmania.

Further analysis of the profiles indicates that there are no observable anomalies in the region of positive Gore analysis and that, in any case, the lateral sampling resolution in the available datasets is not high enough to allow for the discrimination of anomalies of the type described by Wolleben & Greenlee 2002, LeSchack & Valasteen 2002, Berger et al 2002 and Donovan et al 1979. In order to carry out analysis of this kind micromagnetic profiles would need to be acquired across the region allowing for the characterization of both high and medium frequency anomalies as described above and by Wolleben & Greenlee 2002.

Gravity modeling of potential fault offsets in the Seymour region

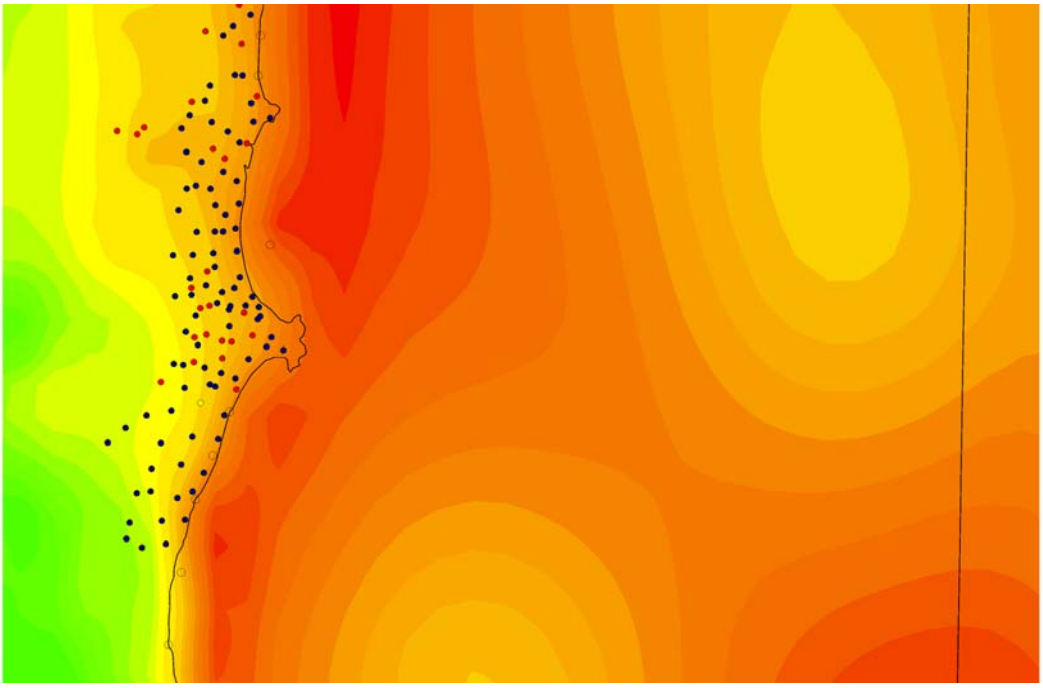


Figure 4 – Bouger gravity image for the Seymour region.

An additional aim of this work was to assess whether there was any possibility of estimating throw on the basin bounding fault to the west of the possible reservoir in order to assess the potential reservoir depth and thus volume.

A number of profiles were loaded into a gravity 2.5 forward modeling package and an assessment was done on the value of running a series of scenarios. Unfortunately, once again the resolution of the available gravity datasets in the region of interest, along with a lack of constraining geometric data at depth and few density measurements do not allow for constrained forward models of the type that would give us confidence in the results.

Figure 4 shows the gridded gravity data from the region and the smooth gradients indicate that features at the scale of interest (which would produce higher frequency responses) have not been resolved and so can not be modeled accurately.

Conclusions

1. The available magnetic line data is not high enough resolution to allow micromagnetic analysis of the type proposed by Wolleben & Greenlee 2002 or Donovan et al 1979.
2. There are no observable magnetic anomalies that can be attributed either to the faults in the target region or to fluid or hydrocarbon migration along these faults.
3. The Gore sampling did suggest that there may have been leakage of hydrocarbons along the faults described in previous reports. As the micromagnetic techniques described above have the potential to define the extent of buried reservoirs and associated seeps, there is potential to acquire new data of the required resolution and interpret it as described by the aforementioned authors.
4. This would require commissioning of a geophysical company with the appropriate equipment to fly several lines over the target region and a contractor familiar with the technique and workflow to process and interpret the resultant data. Whist cheaper than acquiring seismic this would be a costly undertaking with no guarantee of success.
5. Given the lack of additional data constraints from the available geophysical data we are really back where we started. In summary there are known structures in the region and there is a know source. The migrations pathways are not well understood and the geometry and volume of any potential reservoir is poorly constrained. The Gore samples indicate there has been hydrocarbon seepage in the region and this correlates with the known gas emitting wells in the region and other anecdotal evidence such as hydrocarbon slicks forming in local waterways from time to time. My personal feeling is that this play is a long-shot with just enough of a sniff to prevent us from dismissing it. Making any more of a call than this is **not** my area of expertise however and I suggest that you seek further technical advice before making any decision regarding relinquishment or spending additional money on the ground.

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Recent Developments in Magnetic Method for Hydrocarbon Exploration

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Summary

Technological advancement in magnetometers has resulted in the possibility of measuring the magnetic field with high accuracy; to add to this the improvement in the positioning of the aircrafts using GPS, compensation software / hardware for suppressing airplane noise and gradiometer measurements have led to a sea change in the kind of resolution that can be achieved in the study of aeromagnetic anomalies. This combined with the availability of sophisticated computers and data processing and imaging techniques has made it possible to identify and interpret the miniscule magnetic signatures associated with hydrocarbons. Further, there has been a global surge in geochemical studies to understand magnetic mineralogy, in particular those associated with hydrocarbon seepage and migration that could result in weak magnetic signatures. Thus a combination of recent developments in various fields has resulted in making the Magnetic Method 'a Tool to reckon with', for hydrocarbon exploration. Global examples of the different types of surveys and the resultant improvement in magnetic data interpretation related to hydrocarbon exploration will be presented.

Introduction

The Magnetic Method has for a very long time contributed in assisting oil exploration, mainly as a secondary reconnaissance tool, by helping to define the basement structures that control emplacement of hydrocarbon in overlying sedimentary basins. Although advances made in acquisition, processing and interpretation of aeromagnetic data were being widely applied to the exploration of minerals and geothermal resources, there was a lull in the application of the magnetic method to petroleum exploration in the mid seventies. However, in the recent past, technological advancement in instruments, better data collection procedures, associated data interpretation / imaging techniques and better understanding of magnetic mineralogy has promoted the magnetic method from a reconnaissance tool to a method that a specialist needs to consider seriously for the purpose of hydrocarbon exploration.

Technological Advancement of the Magnetic Method

Improvement in the instrumentation technology has led to the development of accurate magnetometers; the currently available Cesium vapor Magnetometers and Overhauser Magnetometers are able to measure data with an accuracy of 0.001nT. The SQUID magnetometer is one of the most sensitive measurement devices known to man. SQUID or Superconducting Quantum Interference Devices, measure extremely small magnetic fields as small as 10^{-15} Tesla or one femto-Tesla. With the availability of gradiometers measuring horizontal and vertical gradients in the total magnetic field, it is possible to enhance the gradients of the observed weak magnetic anomalies and thereby map lithological / geological structures prospective for hydrocarbon exploration, very accurately. This coupled with precise aircraft positioning using GPS and software / hardware for suppressing airplane noise has resulted in marked improvement in the data acquisition quality and resolution. Blakely (1995) describes in detail the various possible data processing techniques including forward and inverse modeling for analysis of magnetic data. With the availability of sophisticated computers and data processing and imaging techniques, the interpretations have improved manifold and have contributed to a quantum jump in the application of aeromagnetic data to hydrocarbon exploration. Thus, major strides have been made in the acquisition, processing and interpretation of aeromagnetic data.

One of the major problems in the application of magnetic methods is the isolation of weak magnetic anomalies caused by low concentrations of the magnetic minerals in sediments. These weak anomalies are often masked by much stronger magnetic anomalies caused by underlying magnetic rocks and/or by rocks in the sedimentary basin. Proper filtering techniques need to be applied to isolate the signal from the noise; the weak anomalies can be effectively isolated by applying selective band pass filtering filters. It maybe noted that for aeromagnetic data, the along flight data spacing, flight altitude and flight line spacing play an important role in the resolution of the data collected. Available aeromagnetic data over India at the reconnaissance scale (1:250,000) are collected at a flight altitude of around 1.2 km with a flight line spacing of 4 km. with sample spacing of 20m and accuracy of 0.1 nT (Rajaram et al, 2006). Whereas, High Resolution Aeromagnetic (HRAM) data for petroleum exploration are commonly defined as data collected at a flight line spacing of 800m or less at flight heights of 150m or less, at 15 m or less sample spacing along the flight line and at better than 0.1nT accuracy (Glenn and Badgery, 1998). Several countries have repeated their aeromagnetic surveys keeping pace with the technology especially in regions of viable resources. Helicopter mounted system can be used in areas with strong topographic effects as these can be flown while draping the landscape, and as such, minimize the effect of topography. Super HRAM data is collected from a helicopter platform; according to Image Interpretation Technologies Inc. (2005), for SHRAM, typically the data is collected at 30 – 50 m above the ground and with 50 – 200 m flight line spacing. By flying closer to the ground with decreasing flight line spacing, there is a dramatic increase in resolution; the helicopter-borne SHRAM data can detect even the subtlest sedimentary magnetic anomalies that are created in the shallow sedimentary section.

Magnetic Mineralogical Studies

The International Association of Geomagnetism and Aeronomy has declared the current decade as the Decade of Geopotential Research. Several Satellites dedicated to making measurements of the geomagnetic field have been put in orbit, during this period. This has ushered in a global interest in understanding the cause of the geomagnetic anomalies and resulted in intricate geochemical studies to understand magnetic mineralogy. Of particular interest in this regard is the understanding of the changes in magnetic mineralogy caused by hydrocarbon seepage and migration that could result in weak magnetic signatures. The hydrocarbons leak in varying quantities to the surface and produce, through geochemical interaction, magnetic minerals in the sediments. The process commonly associated with and generated by hydrocarbon micro-seepage include the authigenic precipitation of pore filling carbonate cements, which may decrease permeability of sealing cap rock and the diagenetic, largely microbial conversion process of weakly magnetic hematite parent mineral to strongly magnetic magnetite (Stone et al, 2004). Authigenic magnetite maybe generated in at least two ways: Reduced iron combines with hematite and water to form magnetite and secondly, iron reduced at some depth migrates upwards into an oxidizing zone and oxidation would directly produce magnetite and maghemite (Donovan et al, 1984). The magnetic contrast between sedimentary rocks of normally low magnetic susceptibility and those locally enriched with this epigenetic magnetite results in distinctive magnetic signatures resulting in characteristic “magnetically enhanced zones” which have proven invaluable in hydrocarbon exploration. In China, soil magnetic measurements (susceptibility and hysteretic parameters) and soil hydrocarbon analysis were conducted near the Jingbian gas field and their results provide strong evidences for the formation of highly magnetic minerals in close association with hydrocarbon seepage (Liu et al, 2004). Recognition of such seepage induced magnetic anomalies can be used to facilitate the exploration of oil and gas. Enrichment of magnetic mineralization due to hydrocarbon migration is also a well know phenomenon (see articles in Schumacher and Abrams, 1996).

Urquhart (2004) states that “Bacteria and other microbes play a profound role in the oxidation of migrating hydrocarbons. Their activities are directly or indirectly responsible for many of the diverse surface manifestations of petroleum seepage. These activities, coupled with long-term migration of hydrocarbons, lead to the development of near-surface oxidation-reduction zones that favor the formation of hydrocarbon-induced chemical and mineralogical changes. This seep-induced alteration effect has led to the development of a varied number of geochemical exploration techniques. Some detect hydrocarbons directly in surface and seafloor samples, others detect seep-related microbial activity, and still others measure the secondary effects of hydrocarbon-induced alteration using magnetic techniques”. He discusses the Sedimentary Residual Magnetic (SRM) anomaly method which depends on the magnetic properties of the rocks in the sedimentary section being changed by the presence of hydrocarbons at depth; these changes produce magnetic anomalies that are distinguishable from anomalies produced by the magnetic basement and other effects. The test studies show that in practice the method will enhance the success rate of an exploration program where the SRM method is incorporated into the methodology

Examples

An excellent example of the utility of improving resolution of aeromagnetic data is available from the Western Canada Sedimentary Basin (WCSB). The Geological Survey of Canada (GSC) had collected data over WCSB at the reconnaissance scale. Subsequently, magnetic surveys of this Basin have been carried out extensively, at different resolutions. Hassan (2003) of GEDCO, has made a comparison of the HRAM data and GSC data collected over the WSCB and finds that the GSC data does not have adequate frequency content to solve structural problems except on very regional scale while the HRAM data could resolve faults both in the basement and in the sedimentary section and allow one to map the basement. Further, selected areas of WCSB were re-flown using helicopter to collect SHRAM data. Image Interpretation Technologies Inc. (IITech, June 2005) have compared the HRAM and SHRAM data sets; a thrust fault identified in the HRAM data appeared to be offset in a sinistral sense suggesting a tear fault in the sedimentary section. However, the better resolution of the SHRAM data suggested a lateral ramp in the hanging-wall of the thrust, rather than a tear fault.

Several examples to demonstrate the enhanced resolution achieved in the magnetic anomalies that could be used for hydrocarbon exploration purposes, will be presented.

Conclusions

The integrated efforts of Engineers, Geophysicists, Computer Scientists, Petrologists and Geochemists amongst others have resulted in transforming the Magnetic Method for Hydrocarbon exploration from a mere reconnaissance tool to a method that can now provide levels of detail that are compatible to those derived from seismic, well and surface geological data. The Magnetic Method is here to stay!!

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Successful Application of Micromagnetic Data to Focus Hydrocarbon Exploration

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ABSTRACT

Low-level, high-resolution aeromagnetic data acquired along closely spaced flight lines provide information that can be used to detect magnetic enrichment produced by vertical microseepage from hydrocarbon traps. Aeromagnetic data acquired prior to drilling display characteristic micromagnetic hydrocarbon signals over areas in which significant production is later established. Three examples of newly discovered west Texas Pennsylvanian production, one example of Jurassic production in Alabama, and examples of various fields in Texas Railroad Commission District 4 are presented. Seismic and aeromagnetic data from an unsuccessfully drilled micromagnetic lead are reviewed, and aeromagnetic data over large nonprospective areas are displayed. To date, 87% of the micromagnetic leads that subsequently have been drilled have yielded economically successful fields or field extensions.

INTRODUCTION

High-resolution aeromagnetic surveys can provide the oil and gas industry with a low-cost exploration technology that can be used to locate significant hydrocarbon accumulations. An increasing body of published literature (Elmore et al., 1989; Elmore and Crawford, 1990; Reynolds et al., 1990b; Machel and Burton, 1991a; Ellwood and Burkart, 1996) indicates that a direct relationship often exists between hydrocarbon accumulations and near-surface magnetic enrichment. Improvement of aeromagnetic data acquisition techniques and development of computer capabilities to evaluate this type of data have produced the information required to generate micromagnetic exploration "leads."

A 15-year investigative period, from 1984 to 1999, provided a unique opportunity to evaluate the success rate of wildcat wells drilled on micromagnetic leads and, more important, to document the cumulative production history of many of these successfully drilled prospects. To date, 87% of the micromagnetic leads that subsequently have been drilled by various operators have yielded economically successful fields or field extensions (63 micromagnetic leads have led to 55 new fields or extensions). Success rates for individual wells are higher (405 successful wells and 51 dry holes = 89% success). This statistically significant relationship indicates that micromagnetic analysis is a powerful exploration technology that can be used

- as a *focusing tool* to locate significant accumulations of hydrocarbons or
- as a *confirmation tool* to supplement other exploration methods (e.g., seismic surveys and subsurface geology) in defining hydrocarbon traps

ACQUISITION AND PROCESSING OF MICROMAGNETIC DATA

In typical high-resolution surveys, aeromagnetic flight lines are flown at low levels (300–500 ft, or 90–150 m, above the surface), and the magnetic field is sampled every 0.10 to 0.25 seconds (s) with the cesium magnetometer. Flight lines are usually spaced 0.25 mi (0.4 km) apart in one direction and 0.25 mi (0.4 km) apart in the orthogonal direction. Total-intensity magnetic profiles are generated from the flight-line digital data, and these profiles are stacked in their proper geographic relationships.

Individual total-intensity profiles are studied carefully, using all available supplemental information. A videotape recording made along each flight line provides an exact visual record of surface conditions at the time of data acquisition. Both surface and subsurface geologic information, when available, along with topographic data, also greatly enhance profile evaluation.

ANALYSIS OF MICROMAGNETIC DATA

Micromagnetic analysis uses geophysical data to detect near-surface magnetic enrichment produced by vertical microseepage from hydrocarbon accumulations. The formation of magnetic minerals associated with hydrocarbon seepage has been discussed by numerous authors in the past two decades (Elmore et al., 1987; McCabe et al., 1987; Henry, 1989; Leach and Elmore, 1989; Henry and Tomlinson, 1991; Machel and Burton, 1991b; Saunders et al., 1991; Schumacher and Abrams, 1996). Saunders et al. (1999) note that various investigators have reported all the magnetic forms of iron oxide and sulfides among the diagenetic minerals over petroleum fields, including maghemite (Foote, 1996), magnetite (McCabe et al., 1987), and pyrrhotite and greigite (Sassen et al., 1989; Reynolds et al., 1990a; Machel and Burton, 1991b; Machel, 1996).

The micromagnetic profile is a composite that consists of the summation of magnetic signals derived from different sources (e.g., long-wave-length basement-derived signals; intermediate-wavelength intrasedimentary signals; and short-wavelength, high-frequency, surface- or near-surface-derived signals). Each type of signal must be identified and considered when each profile is studied. Several types of oft-occurring signals have been recognized in the studies we have completed. Single cultural features (e.g., houses, cars, pump jacks, surface casing, windmills, and the like) usually occur as a spiky signal on one or two profiles. Areas with a high density of cultural features, such as a preexisting oil or gas field, always produce highly distorted profiles. Linear cultural features (e.g., pipelines, railroads, highways, and power lines) produce a similar signal on multiple profiles. Certain geologic conditions can produce concentrations of magnetic minerals that are related to recent surficial geologic processes (e.g., glacial moraines, fluvial depositional systems, solution of carbonates and concentration of magnetic minerals in canyon lands, and heavy mineral concentrations on barrier islands). These geologic magnetic concentrates are easily recognized when surface and near-surface geologic relationships are integrated into the micromagnetic analysis.

Diagnostic micromagnetic signatures indicate the presence of secondary magnetic minerals that are formed by either chemical or bacterial processes in the hydrocarbon seepage chimney. These characteristic micromagnetic hydrocarbon signatures show gradual increases and decreases in signal (Figure 1), flight-line-to-flight-line similarity in signal (Figure 2), and similar signal responses on orthogonal flight lines (Figure 3). Examples in the following case histories demonstrate all the aforementioned signal attributes, and all have geometric outlines that approximate the productive reservoir geometries.

Micromagnetic data are geophysical data and are similar to seismic and gravity data because they are a repeatable measurement of one of the earth's physical properties. Magnetic enrichment over a hydrocarbon trap is produced by microseepage over a geologically long period of time. Magnetic minerals in the enriched zone are usually unaltered by short-term ambient conditions; therefore, they should be detectable in any properly flown survey. Numerous examples of repeatability can be demonstrated, and two are presented in Figure 4.

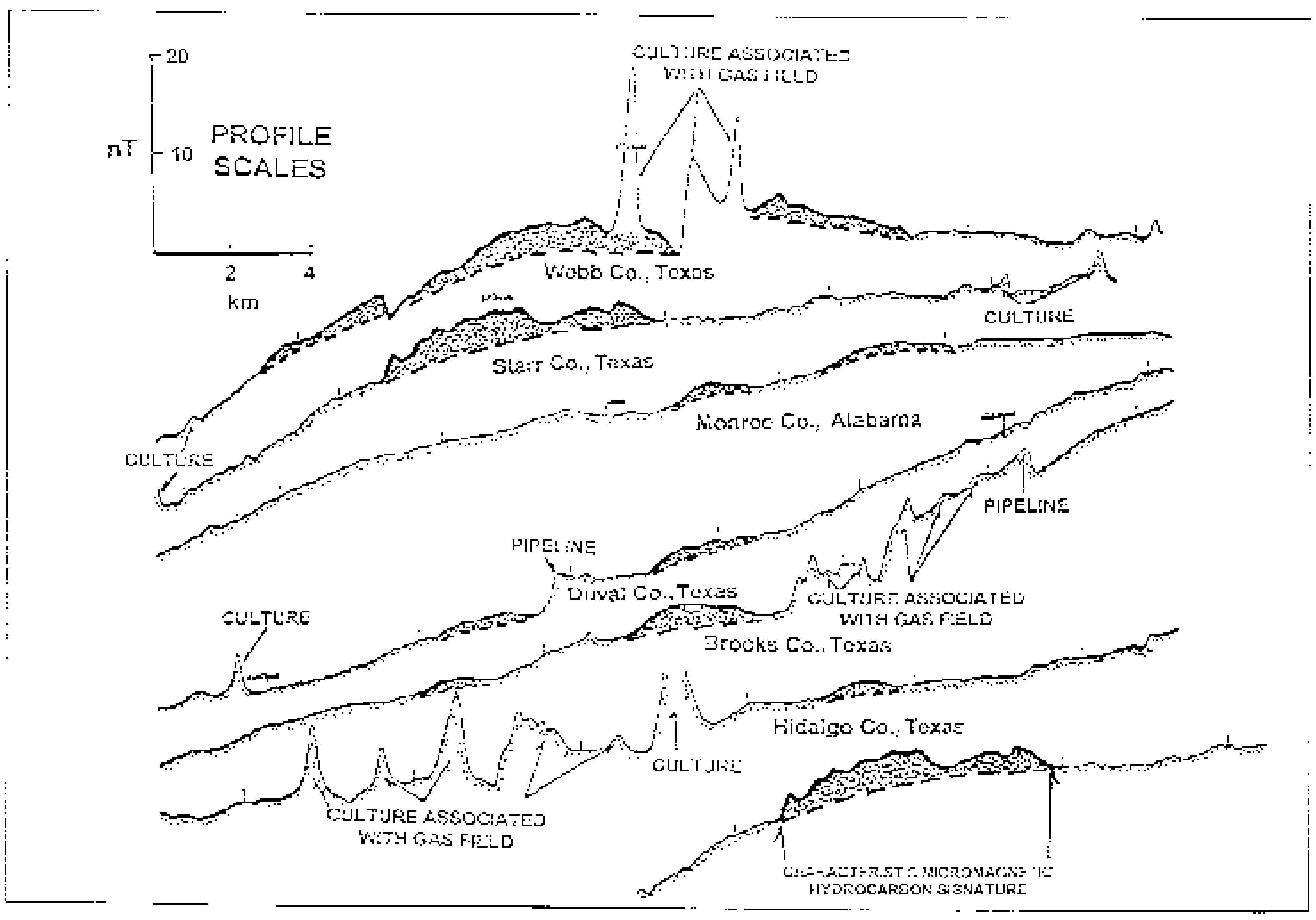

FIGURE 1. Total-intensity profiles over various micromagnetic hydrocarbon prospects. Profiles display gradual increases and decreases of magnetic signals, a pattern that is characteristic of microseepage from hydrocarbon traps.

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Integrated Analysis of High-resolution Aeromagnetic (HRAM) and RADARSAT-1 Imagery for Exploration in Mature and Frontier Basins

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ABSTRACT

This paper illustrates the use of an integrated analysis of HRAM data and RADARSAT-1 images for detection and analysis of geologic structures in mature and frontier basins. The HRAM images provide detailed information on basement structures, weakly magnetic faults, and fracture systems in the sedimentary section, and other features that contain magnetic material anomalous to the surrounding rock units. The RADARSAT-1 images are used to constrain the analysis of the HRAM data, as well as to expand the interpretation into areas that are not covered by the HRAM surveys. A series of examples supported by surface and subsurface controls has been used here to illustrate our integrated approach to the analysis of these two reconnaissance exploration tools.

In the shallow waters of the Gulf of Mexico, HRAM images are used to map the inventory of complex salt bodies and to establish their structural linkage with extensional, listric, normal fault systems. In the foothills region of northeastern British Columbia, the integration of HRAM images and RADARSAT data leads to the recognition of (1) exposed and buried folds and thrust faults, which form the key hydrocarbon traps of this region, and (2) major cross-trending fault zones that form a fractured-reservoir fairway.

Finally, in a frontier exploration area (the onshore basins of Gabon), we have used newly available HRAM data, RADARSAT-1 images, and regional seismic data to investigate the hydrocarbon potential of deep-seated basement structures in the Dianongo Trough. The regional coverage of the HRAM data and RADARSAT images allows us to establish the structural style of different parts of the basin, identify new exploration concepts and leads and, most important, map key basement structures that lie below the salt layers of this basin. Previous attempts to explore for such subsalt plays were hindered by the poor quality of the seismic data for these exploration targets.

INTRODUCTION

Airborne magnetic data have been used in petroleum exploration for many years, and in the last decade, we have seen a renaissance in the use of this geophysical reconnaissance tool. In addition to detecting basement structures, high-resolution aeromagnetic (HRAM) surveys detect weakly magnetic faults and fracture systems in the sedimentary section, as well as other subsurface geologic features, such as salt domes and paleostream valleys, that contain material magnetically anomalous to the surrounding rock units (e.g., Peirce et al., 1998; Reid, 1998; Spaid-Rietz and Eick, 1998; Berger, 1998; Kivior and Boyd, 1998; McConnell 1998).

Although the analysis of deep-seated structures seen in HRAM data is best constrained with well and seismic data, the high-frequency features seen on these images are best constrained through the integration of surface information from topographic maps, surface geologic maps, and RADARSAT-1, Landsat, and other remote-sensing imagery (e.g., Berger and Davies, 1999). Our experience with integrated HRAM data interpretation has led us to recommend RADARSAT-1 data as the preferred remote-sensing tool for the integrated analysis of surface and near-surface structures.

Satellite and airborne radar images are both particularly useful for mapping surface structures in the tropics and other heavily vegetated areas, for four main reasons. First, images of the earth's surface can be obtained through the heavy cloud cover prevalent in the tropics and subtropics because radar uses much longer wavelengths than visible sensors use. Second, radar-imaging systems have proved to be excellent surface-mapping tools in tropical and temperate areas because the systems are sensitive to variations in topography and surface roughness, and thus are capable of imaging the topographic expression of structures that are completely obscured by vegetation and other surficial material. Third, the shadowing effect that results from the radar's side-looking nature greatly enhances the surficial expression of structures on the image. This effect can be maximized by carefully selecting the beam alignment to look perpendicular to preferred structural orientations (relative to both slope and aspect). Fourth, images taken over the same area, using different incidence angles and the same look direction, can be combined to obtain a stereo image that also improves the structure-mapping capabilities of radar (e.g., Ford et al., 1983; Drury, 1987; Sabins, 1987; Harris, 1991; Berger, 1994; Ellis et al., 1994). The advantage of satellite data over airborne radar is that the RADARSAT-1 system provides affordable digital global coverage (RSI, 1996).

OBJECTIVES

This chapter has three objectives. First, we wish to introduce the reader to the unique structure-mapping capabilities of HRAM surveys, particularly in regard to their ability to detect structures at the sedimentary level. Second, we will illustrate the role of RADARSAT-1 imagery in the integrated analysis of HRAM data. Finally, we will illustrate our approach to structural interpretation of HRAM data, using an example from Gabon.

Culminating in a frontier case study of the Dianongo Trough area of Gabon, this paper provides examples of integrated HRAM interpretation from mature regions such as the Canadian fold-and-thrust belt, the Canadian Shield, and the Gulf of Mexico. Salt-related features found in the Gulf of Mexico provide insight into similar features found in the Dianongo Trough region and their influence on the development of hydrocarbon traps in south-central Gabon.

It must be stated that the approach presented in this paper for the integrated analysis of HRAM data focuses primarily on the structure-mapping capabilities of these surveys as they exist, qualitatively, in combination with other surface and subsurface data. These studies, however, can also be supplemented by more-quantitative potential-field-interpretation techniques, such as depth-to-basement mapping, depth-to-source analysis, and magnetic-profile interpretations (e.g., Best et al., 1998; Goussev et al., 1998).

DETECTING SEDIMENTARY AND BASEMENT STRUCTURES USING HRAM DATA

The power of HRAM data as a structure-mapping tool is illustrated in Figure 1, which shows a color-shaded HRAM image of the Canadian Shield. The image, generated from survey data flown at 200-m line spacing and a flying altitude of 60 m, shows two types of exposed basement features. The color components of the image express variations in the magnetic intensity (susceptibility) for different basement lithologies. Curvilinear, high-frequency features reflect faults, fracture systems, dikes, and other small-scale, basement features. Note that the data allow us to identify the edges of high-frequency features almost continuously, with very few "smearing" or aliasing effects. This is crucial for detailed structural analysis, and results directly from tight line spacing and advanced processing and imaging techniques.

Figure 2 shows a gray-scale image of HRAM data that were collected over the shallow water of the Gulf of Mexico, offshore Louisiana. The HRAM data capture the magnetic expressions of salt domes and walls, as well as listric normal faults that connect many of the salt features. Salt features have a strong expression on magnetic images because their susceptibilities are significantly lower than those of surrounding rock units. The salt bodies identified on HRAM data correlate well with those observed with

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High-resolution Ground-magnetic (HRGM) and Radiometric Surveys for Hydrocarbon Exploration: Six Case Histories in Western Canada

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ABSTRACT

In Western Canada, and probably elsewhere around the world, "magnetically enhanced zones" above microseeping hydrocarbon reservoirs can exhibit distinctive magnetic signatures that are characteristic of the reservoir. These distinctive magnetic signatures have proven to be invaluable for hydrocarbon exploration, and we have achieved 85% exploration success using ground-based magnetic and radiometric techniques in Western Canada. Differences in timing and duration of microseepage and differences in composition and pressure of the microseeping hydrocarbon gases from separate petroleum systems probably control the magnetic mineralogy, magnetic grain-size distributions, magnetic susceptibility, and natural remanent magnetization (NRM) directions in the magnetically enhanced zones. Together, these differences can yield diagnostic "residual" (remanent + induced) short-spatial-wavelength magnetic anomalies above different reservoirs.

Whereas our magnetic surveys are measuring *fossil* anomalies at depths of about 150 m, our radiometric surveys are measuring *modern* geochemical alterations at depths <25 cm. Thus, finding both magnetic and radiometric anomalies at the same location implies not only that a microseeping hydrocarbon reservoir once existed below, but also that it is still there and still leaking. In this study, we present six case histories from Western Canada in which our combined magnetic and radiometric surveys were effective for hydrocarbon exploration.

Our high-resolution ground-magnetic (HRGM) surveys have sufficiently high resolution that residual magnetic anomalies commonly appear to be dipolar in Western Canada. Nearly equal intensities for the positive and negative lobes of the anomalies, and major departure of the dipole axes from present magnetic north, imply that (1) about half the intensity of the residual anomalies represents remanent, rather than induced, magnetization; and (2) a significant proportion of the remanent magnetization is "reversed polarity" and hence is older than the most recent geomagnetic reversal at 0.78 Ma.

In the prolific Devonian reservoirs of Western Canada, much of the reversed-polarity magnetization probably dates from a strong "reversed-polarity-bias interval" that prevailed during the early Tertiary, from 63 to 41 Ma. At that time, generation of hydrocarbons, rapid subsidence, and the regional topographic hydrodynamic drive created high pore pressures that facilitated regional vertical fracturing of the Laramide foreland. Above reservoirs where oil was trapped during early Tertiary migration, buoyant hydrocarbon microbubbles began to rise along the regional, vertical microfractures. At higher structural levels, the microseeping hydrocarbons caused magnetic minerals to precipitate (by inorganic and/or biogenic processes) in magnetically enhanced zones, thereby recording early Tertiary, reversed-polarity remanent magnetization. Later in the Tertiary, a second generation of magnetically enhanced zones probably was created after maximum burial, at peak overpressure, and when methane began to exsolve by pressure reduction during isostatic uplift.

In Western Canada, the strongest HRGM anomalies occur above the deepest, most prolific reservoirs at the highest pressures, and the weakest HRGM anomalies occur above shallower, less-productive reservoirs at lower pressures. In the Alberta Basin, the HRGM anomaly intensity decreases monotonically, from highest values over prolific Leduc Formation (Upper Devonian) pinnacle-reef reservoirs, to somewhat lower values over Nisku Formation (Upper Devonian) biostrome reservoirs, to still lower values over less-productive Cretaceous blanket/channel-sand reservoirs, to lowest values over dry and abandoned (D&A) wells. In the Williston Basin, strong HRGM anomalies occur above Mission Canyon Formation (Mississippian) limestone cuesta reservoirs, whereas no HRGM anomalies (only radiometric anomalies) occur above shallower lower Amaranth Formation (Triassic?) channel-sand reservoirs. The stronger HRGM anomalies above the deeper Devonian and Mississippian reservoirs may reflect (1) *higher concentrations* of authigenic magnetic minerals in the magnetically enhanced zones; (2) *more focusing* of vertically ascending microbubbles by the more nearly point-source pinnacle reef and cuesta reservoirs, compared with more spatially diffuse blanket/channel-sand reservoirs; and (3) *shallower depths* of magnetically enhanced zones as a result of higher pressure within the deeper reservoirs.

For hydrocarbon exploration, the distinctive magnetic signatures revealed by high-resolution ground-magnetic surveys have an important practical application: We find that the HRGM anomaly intensity and the residual magnetic-anomaly azimuth can identify the reservoir that is causing the anomaly. We illustrate this principle in three case histories in the Williston Basin and three case histories in the Alberta Basin. Although all six of these case histories are from Western Canada, ground-magnetic surveys would probably be equally successful worldwide, especially where hydrocarbon microseepage has occurred during the Tertiary (65 to 1.8 Ma), when the geomagnetic field exhibited reversed-polarity bias.

Case histories 1 and 2 document three new oil-field discoveries, based on magnetic and/or radiometric anomalies over lower Amaranth and Mission Canyon reservoirs near Pierson, Manitoba. Case history 3, at the Waskada field, Manitoba, is an after-drilling study, in which the HRGM survey delineates Mission Canyon limestone reservoirs and the radiometric survey delineates productive channels in the overlying lower Amaranth sand. Case history 4, another after-drilling study, documents that an HRGM survey and a 3-D seismic survey are equally effective in targeting a Leduc pinnacle reef at the Rumsey field, Alberta. Case histories 5 and 6 cover 10^4 ha in central Alberta, including 55 Cretaceous producers, 15 Nisku producers, and 22 abandoned wells. After-drilling comparison of the magnetic data with the production data reveals that the HRGM surveys could have been used to predict the producers and to avoid the dry holes.

Statistical comparisons of high-resolution ground-magnetic (HRGM) with high-resolution aeromagnetic (HRAM) data and verification with ground data of a specific HRAM anomaly in central Alberta reveal that airborne and ground-magnetic surveys can be used together, cost-effectively, for hydrocarbon exploration. Reconnaissance HRAM surveys are especially useful in targeting prospects for further, more-detailed evaluation by HRGM/radiometric surveys. In Western Canada, combined HRGM and concurrent radiometric surveys have been highly successful in finding hydrocarbons, and the total cost, including permitting, is about 20% the cost of a 3-D seismic survey over the same area. These surveys complement traditional exploration methods, substantially reduce finding costs, and significantly increase the probability of exploration success.

INTRODUCTION

Aeromagnetic surveys over sedimentary basins have been used for decades for mapping basement structure and depth. Only relatively recently, however, have such surveys been used for *directly* locating hydrocarbon reservoirs by identifying shallow, diagenetic magnetic anomalies produced by upward-leaking hydrocarbon gases. For example, Donovan et al. (1984), Foote (1986a, b, 1992, 1996), Andrew et al. (1991), Foote et al. (1997), and Wolleben and Greenlee (2002) have shown, in a variety of ways, the applicability of *high-resolution aeromagnetic* (HRAM) surveys for mapping such anomalies.

Based on the encouraging results of the early airborne magnetic studies, author LeSchack developed a *high-resolution ground-magnetic* (HRGM) survey technology (LeSchack, 1994, 1997) that reveals excellent correlation between hydrocarbon reservoirs and small (1–12-nT) near-surface magnetic anomalies in Western Canada. Concurrently with the development of the magnetic survey technology, a ground-based radiometric survey technique, adapted largely from Saunders et al. (1993a), was also developed to complement the ground-based magnetic surveys. The magnetic and radiometric surveys detect, by geophysical methods, geochemical alterations caused by vertical microseepage of hydrocarbons.

In this paper, we present six case histories in which HRGM and radiometric surveys were used, cost-effectively, for hydrocarbon exploration in Western Canada. Generally, our ground-based magnetic/radiometric surveys were being used in conjunction with more traditional geologic and seismic methods for evaluating prospective areas, verifying seismic anomalies, and inexpensively targeting areas for conducting expensive 3-D seismic surveys. Occasionally, as in two of the case histories in which seismic exploration is not effective, our magnetic/radiometric surveys were used successfully as a stand-alone exploration method. Of the six case histories, three are examples in which our surveys were conducted prior to drilling. These before-drilling surveys resulted in discovery of three new oil fields, based on subsequent drilling of magnetic and/or radiometric anomalies.

In addition to presenting the six case histories, we verify that the subtle, shallow, short-spatial-wavelength magnetic anomalies that are mapped by our HRGM surveys are commonly also present in HRAM surveys. To illustrate this, we present a comparison of an HRGM survey with an HRAM survey flown over nearly the same area in central Alberta. Although this comparison reveals some of the limitations of using HRAM data alone for mapping shallow anomalies, it demonstrates how airborne surveys can be used to target higher-resolution, ground-based surveys to better define prospects.

THEORETICAL BACKGROUND

The case histories discussed in this paper are part of a growing body of evidence that relates surface and near-surface anomalies in magnetics, topography, potassium, uranium, and seismic velocities to microseepage from underlying hydrocarbon reservoirs. Microseepage from hydrocarbon reservoirs is thought to occur by nearly vertical ascent of colloid-size microbubbles of light hydrocarbons (methane through the butanes) through a network of interconnected groundwater-filled joints, fractures, and bedding planes (Saunders et al., 1993a, b, 1999, 2002; Thompson et al., 1994). Chemical and/or bacterial degradation of microseeping hydrocarbons instigates diagenetic changes that alter the near-surface magnetic mineralogy, the concentration of uranium and potassium minerals, and the seismic properties of lithologies overlying the microseeping reservoirs. Machel and Burton (1991a) concluded that in hydrocarbon microseepage environments, bacterial and chemical processes most commonly produce magnetite or pyrrhotite and destroy hematite.

Hydrocarbon microseepage has been reported to enhance the magnetic mineralogy over a wide range in *depth*, from surface soils to strata as deep as 1500 m (~5000 ft). Hydrocarbon microseepage can also affect the magnetic mineralogy over a wide range in *time*, from fossil paleomagnetic directions recording the initiation of microseepage to modern magnetic enhancement resulting from presently thriving bacteria.

In surface soils, Saunders et al. (1991) documented that anomalously high concentrations of authigenic magnetic minerals occur just below the grass roots in 89% of cases over 19 oil and gas fields. They identified magnetite spherules, octahedral crystals of magnetite,