ORAL ABSTRACTS

SECTION 3

Day 1: Monday 19 November 2007

10:30–12:30

MINERALS 1.1

Case Histories

MAPPING TARGETS OF HIGH CONDUCTANCE WITH THE VTEM AIRBORNE EM SYSTEM

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The VTEM airborne EM system has been in commercial use since late 2002 and has been applied to a wide range of mineral exploration targets on a global basis. While designed to have a broad-band conductivity response, certain styles of deposits such as magmatic Ni–Cu can show conductances which exceed the measuring aperture of the VTEM system as first designed. In 2006, Geotech Ltd introduced a modified VTEM system which allowed for the enhanced mapping of targets of high conductance. We will present results from a number of such situations showing the comparison of airborne and ground results.

COMPARISON OF 3D CONDUCTIVITY IMAGING FROM MULTIPLE EM SURVEYS

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It is now possible to invert frequency and time domain data to recover 3D conductivity models. The San Nicolas deposit makes an ideal test site because much is known about the deposit and also many different types of survey data have been collected there. In particular DC resistivity, 3D controlled source frequency domain data, and UTEM data have been acquired. We have inverted each of these data sets. In this talk we describe the data sets and the methodologies for inversion and compare the resultant models. The DC resistivity data were not able to see the deposit because of the conductive overburden, but the frequency and time domain inversions produced good images of the primary mineralised zone. Differences between the images, which might be important from an interpretation viewpoint, are generally explainable in terms of survey designs and subsequent resolving power of the experiments. The frequency domain data had one transmitter located 4 km from the survey area while the UTEM data comprised 3 transmitter loops, one of which enclosed the ore zone.

RECONCILING AIRBORNE AND GROUND GEOPHYSICAL OUTCOMES IN THE ATHABASCA BASIN, SASKATCHEWAN CANADA

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The Athabasca Basin, Saskatchewan Canada is the world's premier location of high grade uranium deposits. Most occurrences show a close spatial association with graphite shear-fault zones in the basement rocks (overlain by resistive sandstone) and EM techniques have been used for over 30 years to help map these conductive features. While exploration initially focused on shallower parts of the Basin, current exploration is requiring investigation through thicknesses of sandstone well in excess of 500 m depth. With drilling costs typically now approaching $0.5 million per hole in the deeper parts of the Basin, considerable efforts are being expended to define basement targets with as much spatial resolution as possible. Consequently, most companies are employing some form of ground geophysical surveys to try and sharpen the target focus prior to drilling. We have had the opportunity to compare airborne and ground surveys in a number of locations and have found that there can be considerable disagreement between the conductivity models derived from airborne surveys and those produced from ground EM (active and natural field) or DC resistivity surveys. A number of these examples will be presented and discussed so as to better understand what are the likely sources of error and how best to manage the risk of multiple but non-conforming outcomes.

AIRBORNE GEOPHYSICAL SURVEY OF THE PNG HIGHLANDS AND THE PAPUAN PENINSULA

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The Papua New Guinea Government applied for support under the 8th European Development Fund (EDF) SYSMIN special financing facility on 30 December, 1997. The program is being funded as a grant from the 8th EDF unallocated funds in accordance with the provisions of the ACP-EC Partnership Agreement and in the framework of the Papua New Guinea National Indicative Program. The Mining Sector Support (MSS) Program consists of 10 projects, of which the Helicopter Geophysical Survey of the PNG Highlands and Papuan Peninsula is Project E. This involves the collection of geophysical data using helicopter-borne magnetic and gamma-ray spectrometric instruments over two areas of Papua New Guinea (PNG), where little or no geophysical coverage is available. The availability of these data in both digital and paper-map formats is expected to encourage and facilitate exploration in PNG by international mining companies. Fugro Ltd started flight operations in March 2006. Hevilift, a local PNG helicopter company, is providing two (2) Aerospatiale B3 helicopters and the associated crews. By the end of the first full field season in October 2006, Fugro had completed 82 500 km (39%) of the total of 212 000 km of this program. All of the Year 1 flight area was completed, and flying in the Year 2 area had started. Flight operations in Year 2 area re-commenced in March 2007. The major factors of unpredictable weather and extreme terrain in the survey areas have made this a most demanding program. Data for the Year 1 flying will be presented.

PETROLEUM 1.1

Case Histories

REVEALING THE RESERVOIR: INTEGRATING SEISMIC SURVEY DESIGN, ACQUISITION, PROCESSING AND INVERSION TO OPTIMISE RESERVOIR CHARACTERISATION

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The escalating cost of drilling wells has meant that first class seismic data quality is essential for delineating reservoirs and identifying new well locations in complex geology. This paper describes an integrated workflow which insured that a new 3D seismic dataset acquired off the northwest coast of Australia was designed, acquired, processed and simultaneously inverted to produce enhanced sub-surface image quality over a producing field.

A desire for enhanced production required the geological understanding of the oil field to be improved. The poor quality of existing seismic data made it impossible to accurately identify the top and base of the prime volume carrying reservoir. A new seismic survey was designed with the specific requirement of improving the interpretability of the reservoir away from the wells. Both legacy seismic data and well data were used to aid in the design of the optimal seismic acquisition parameters. This along with single sensor technology produced excellent field data which was further enhanced by a high-end processing flow and inversion. In particular, advanced noise and multiple attenuation techniques have revealed the top reservoir and other previously unseen geological structures. Simultaneous AVO inversion was used to produce rock property volumes of acoustic impedance and Poisson's ratio which demonstrated an extremely high correlation with the well logs further proving the quality of the seismic.

The integration of expertise including geology, geophysics, petrophysics and reservoir characterisation early in the design of this study was the key in producing sub-surface information that allows accurate mapping of the reservoir.

CLOSURE CONFIDENCE: HOW BIG IS THAT FIELD? A CASE STUDY

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This paper presents the results of determining the range of possible areal extents of a field. Defining the extent of a field is geophysically challenging, because the well data usually sample the crest of the structure and not the flanks. PreSDM seismic data provides one view of the depth structure, but cannot provide the range of outcomes necessary for the confidence in the closure to be determined. This paper presents the results of applying a workflow for creating a range of different depth maps so that the confidence in the size of the field can be assessed. Firstly, a cross-validation ('blind well testing') process is used to select a series of depth structures which are a good match to the wells. This is applied to a Monte Carlo selection of different velocity models and layering schemes for the overburden. This provides a high quality set of depth maps which can be regarded as equally likely, which is important for the statistical analysis. Then, an automated full-to-spill volume calculation is performed on each depth map. This gives both a range of possible GRV volumes, and also a range of closing contours. Finally, these closing contours are combined to give a map of probability of the field extent. We conclude that while distance from wells is one important aspect of the closure uncertainty, the difference in structural elevation is also a key control.

APPLICATION OF PRE-STACK DEPTH MIGRATION ACROSS THE ICHTHYS FIELD, BROWSE BASIN

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The giant Ichthys gas-condensate field is located within exploration permit WA-285-P, on the Brewster Platform, in the northern Browse Basin. The field is located approximately 220 km off the coast of northern Western Australia in 260–280 m of water and has been appraised with seven wells and comprehensive 3D seismic coverage. The two main gas pools of the Ichthys Field are the Berriasian Brewster Member of the Upper Vulcan Formation and the mid-Jurassic Plover Formation, located at approximately 4000 m and 4500 m respectively.

Stacking velocity analysis for pre-stack time migration revealed geologically implausible, undulating, RMS velocity patterns at reservoir depths across the main section of the field. Further investigation revealed that the primary cause for the velocity distortions were shallow Tertiary sequences near 1200 m, containing highly contrasting, narrow, elongate velocity anomalies.

INPEX conducted pre-stack depth migration velocity modelling over 1400 km^2 to tackle the velocity issues across the Ichthys Field. A layered/blocky modelling approach with dense residual moveout picking and 3D finite-offset tomography of CGGVeritas enabled the construction of a complex velocity model in the shallow section. Subsequent grid/smoothed velocity tomography with constraints was then used for updating the entire velocity field.

The final derived interval velocity field was more systematically correlated with that observed at the wells and the corresponding depth structure produced from pre-stack depth migration appears to be less complex and more geologically realistic. The resultant velocity model obtained by INPEX is currently being incorporated into the structural evaluation for Ichthys Field.

NEAR SURFACE 1

Engineering

SHALLOW MARINE INVESTIGATIONS IN AUSTRALIA WITH ADVANCED UNDERWATER SEISMIC REFRACTION

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Population growth in Australia and high export demand are driving major infrastructure developments that require subsurface information beneath rivers, in ports and in the near shore marine environments. Conventional geotechnical investigation of these areas with overwater drilling is difficult and expensive. Also traditional shallow marine seismic reflection profiling cannot be used safely in the wave zone and can experience considerable technical problem in very shallow water due to severe multiple production, attenuation and scattering of reflected energy by gas-

charged layers and difficulties of correlating interpreted reflection sections with sub-bottom material properties. These issues have been major drivers of advanced underwater seismic refraction (USR) technologies using static, pulled or continuous underway systems coupled with improved numerical analysis and modelling software that overcome some of the generally accepted limitations of the seismic refraction method.

The advances in USR technologies and their combination with borehole seismic imaging are demonstrated using brief case studies of recent marine infrastructure projects from Western Australia and New South Wales. These projects related to, directional boring, tunneling and port developments. These technologies greatly improve the information that geophysics can provide to geotechnical and design engineers while reducing ground risks to these projects.

TOWARDS DEVELOPMENT OF A RISK MANAGEMENT TOOL FOR ROADS AFFECTED BY DRYLAND SALINITY

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The effect of salinity on roads and other infrastructure is considered one of the measurable effects in economic terms of dryland salinity. Regional maps of the extent of salinity are not appropriate, for management of waterlogging and salinity damage to roads, due to differences in scale and obvious local effects of the road within the catchment. In this study the use of a towed array of electromagnetic instruments was trialled to measure salt concentration beneath the bitumen surface of main roads.

Trials carried out along 10 km of the Great Eastern Highway showed EM surveys along roads were achievable and that the results could be used to focus on the areas that might be impacted by salinity. Further widespread trials were conducted over around 2500 km of roads in the southwest of Western Australia. Analysis of these data was not conclusive due to the lack of data on road construction and age. Direct correlation between conductivity and road condition could not be established and the method still needed some subjective assessment of the results.

An understanding of how the road pavement is affected by shallow saline watertables was considered essential. Geochemical analysis of road pavement affected by salinity in WA indicated there were measurable changes in mineralogy apparently associated with pavement damage. To better understand these effects a short section of the Newell Highway in NSW was surveyed in detail with EM and the road pavement was sampled for a range of conductivities and analysed for engineering and geochemical properties.

SPATIAL DATA DISCOVERY, INTEGRATING A SPATIAL SEARCH SERVICE WITH A GLOBE VIEWER

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Led by Google Earth, globe viewers provide a compelling approach to the visual integration of geospatial data in resource exploration. However, finding and evaluating data from both internal data stores and the vast quantities of data available on the Internet has remained a challenge. Finding spatial data first requires cataloging of those data and associated metadata combined with high-speed spatial and text searches to support data discovery. Evaluation of that data demands responsive visualisation and metadata discovery. This paper discusses the development of a server-based spatial data crawler to build spatial data catalogs, the challenges of scaling large catalogs, optimisation of query performance and the delivery of metadata. We demonstrate how this service has been integrated into an open-source and standards-based globe viewer for use in exploration today.

SHALLOW INDUCTIVE ELECTRIC FIELD RESPONSE MEASURED WITH CAPACITIVE SENSORS

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Modelling software developed shows that a new Capacitive Array Resistivity with Inductive Source (CARIS) method being developed has potential for detecting both conductive and resistive objects and near surface conductivity contrasts. Detecting buried resistive objects has possible application in near surface exploration. Applications could include identification and mapping of chromite and mineral containing quartz veins as well as alteration, silicification. It also shows potential for other near surface applications such as UXO, archaeology, void detection, pipe delineation, or fracture detection. A prototype 100 kHz CARIS instrument has been designed and built. The prototype CARIS instrument has been tested with highly repetitive results under laboratory conditions, showing good comparison with expected results from modelling. Results have shown the ability of the system to reliably detect resistive objects within a conductive uniform half-space (salt water) environment. The CARIS system has also undergone preliminary testing in the field. Initial results from field testing show high repeatability but also high lateral variability. This appears to be due to sensitivity to near surface moisture and consolidation contrasts. Currently a second prototype operating at 5kHz is in production aimed at reducing the sensitivity to soil effects moisture and consolidation effects and increasing the depth of investigation.

13:30–15:00

MINERALS 1.2

Crustal/Regional

DIAMOND EXPLORATION WITH AIRSHIP-BORNE GRAVITY GRADIOMETER

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Early stage diamond exploration commences with the careful selection of geophysical anomalies that are characteristic of kimberlites. However, it is also essential to map the structural controls on kimberlites and the background geology. When used in conjunction with the expected age of emplacement an understanding of the geology helps determine the degree of kimberlite preservation.

This may impact on the economics of a discovery but also provides boundaries on the physical property contrast between the target body and host rock. Historical mapping of the geology of the area around Jwaneng Diamond Mine in Botswana was accomplished utilising a combination of magnetic data and drilling as the region is covered by Kalahari sediments with thicknesses of up to 60 m. A high-resolution airborne gravity gradiometer survey was flown during 2006 utilising the Bell Geospace Air-FTG™ instrument mounted in an airship platform adding important information to the mapping of the complex geology of this area. A major intrusive with a diameter of 25 km dominates the gravity and magnetic response of the area with a dense and highly magnetic inner core. The southern edge of this body is truncated by a trans-continental structure that has been correlated with the Thabazimbi-Murchison Lineament.

KIMBERLITE EXPLORATION USING INTEGRATED AIRBORNE GEOPHYSICS

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Airborne magnetic and electromagnetic surveys together with kimberlite indicator mineral geochemistry have been standard practice in the search for kimberlites. The recent advent of the airborne gravity gradiometer (AGG) showed that airborne gravity gradiometry could also be a successful tool in kimberlite exploration. The installation of a digital AGG system on a helicopter led to the first airborne gravity gradient cum magnetic cum electromagnetic survey. The survey was flown over the central part of the Ekati tenement within the Lac de Gras kimberlite province.

Each of these three geophysical methods relies on a different physical property contrast for its success. A selected sub-area shows that no one method would have identified all known pipes. But all known pipes would have been discovered by integrating all three data sets. The pipes in the selected area are associated with conductivity and/or gravity gradient anomalies; a few with magnetic anomalies.

New data alone are not sufficient to guarantee success in a mature exploration environment. The geophysical data were individually inverted to create 3D density, magnetic susceptibility and electrical conductivity models. Integrating and applying classification techniques to the three 3D models was used in the generation of new targets.

Drill testing of the targets has begun leading to the discovery of a new pipe.

LOOKING LEFT, RIGHT AND CENTRE WITH DHMMR: THREE-COMPONENT B-FIELD DHMMR AT BROKEN HILL, NSW

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The Down-hole Magnetometric Resistivity technique uses a grounded dipole to inject current into the ground and a downhole sensor to measure the resultant magnetic fields. Until recently, the sensor was usually a single component TEM probe. Recently a 12-hole DHMMR program conducted on the North Mine, Broken Hill, used a 3-component B-field 'Atlantis' probe. The results from this survey were spectacular, particularly when considering the target and location: the target was the narrow discontinuous ribbons of low-conductivity Zinc Lodes, located 20–50 m above the highly-conductive main North Mine orebody, and underneath/next to the North Mine infrastructure and development. One risk facing the survey was that the main orebody would act as a short-circuit, causing the impressed current to avoid the Zinc Lodes entirely. To mitigate this, one transmitting dipole electrode was placed down a deep drill hole in a Zinc Lodes intersection and the other was dug into a surface expression of the Zinc Lodes, ~1.5 km south of the drill hole electrode. This layout very effectively isolated and energised the Zinc Lodes mineralisation.

The 3-component B-field probe has a noise level, at the frequencies used in the Broken Hill survey, that is significantly below that of sensors used previously for DHMMR. This resulted in better data and faster acquisition times. Additionally, there is relatively little processing required after the survey to present data in a meaningful manner for interpretation. One final product of the survey was total field geomagnetic data (not utilised to date). The success and accuracy of this survey using new equipment in difficult conditions is expected to lead to a wider and better appreciation of DHMMR's capabilities.

PETROLEUM 1.2

Case Histories

NEAR-SURFACE SEISMIC EXPRESSION OF GAS CHIMNEYS IN THE PERTH BASIN

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Detection of gas chimneys is important not only for the mitigation of risk during the drilling phase, but also in the case of a new prospect, to confirm the presence of an active petroleum system. Gas leaking into shallow strata via gas chimneys can have a significant effect on the physical properties of those shallow strata, changing the seismic and resistivity expression of both the near-seabed strata and the underlying units.

The tendency for the gas to dissipate and attenuate the P-wave energy is well documented, and because shear-wave propagation is less affected, PS reflection sections can be useful in imaging through these chimney regions. However, other physical characteristics are also important. Vertical expulsion of gas can physically and chemically disturb relatively unconsolidated strata, generating a region of chaotic seismic response and altered electrical properties. Shallow gas is also known to generate a karstic expression through chemical reaction of subsidiary gases such as CO_2 and H_2S with the rock matrix, lowering the seismic velocity. On the other hand, biological activity may be enhanced by the presence of the gas, assisting diagenesis, thereby generating a layer of anomalously higher seismic velocity in relatively unconsolidated strata.

We have analysed the expression of apparent shallow gas anomalies in the central Perth Basin as seen on gathers recorded

during the PV91 survey, where a shallow high-speed anomalous layer is located above a gas chimney. Our study models the time and amplitude versus offset characteristics of these seismic events.

THE HYDRODYNAMICS OF FIELDS IN THE MACEDON, PYRENEES AND BARROW SANDS, EXMOUTH SUB_BASIN: IDENTIFYING SEALS AND COMPARTMENTS

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The Barrow Group strata (Macedon, Pyrenees and Barrow sands) of the Exmouth Sub-basin host significant accumulations of gas and liquid hydrocarbons. There is currently production from the Macedon Sands at Enfield and ongoing development drilling at Stybarrow. Active appraisal and exploration is underway, including the mutli-field Pyrenees Development. In the course of assessing these discoveries, BHP Billiton and its joint venture partners have undertaken a hydrodynamic study in order to better understand the sealing mechanisms, the position of free-water-levels (FWLs), and the likelihood of compartmentalisation within the discoveries.

Whilst the region is faulted with a predominant southwest-northeast grain, the potentiometric gradient is surprisingly flat indicating that the individual sands are hydraulically well connected. Other than the Macedon Gas Field, there is no pressure data that indicate intraformational seals have been breached. Thus, top and bottom seal capacity is likely not limiting pool size. Rather, structural spill points and fault seal capacity appear the significant factors in determining pool geometry, with the underlying aquifer being regionally connected around fault tips.

On the field-scale, the flat hydraulic gradient allows for the calculated FWLs to have a high confidence. Pressure data from the hydrocarbon phases indicate that in some cases, fault zones effectively compartmentalise a field into multiple pools. The Macedon Gas Field, on the eastern edge of the play fairway, marks a change in the trapping character with intraformational and fault seals having been breached resulting in a single continuous gas pool despite internal structural complexity.

DEEPWATER TARANAKI: (THE BASIN WITH NO STRUCTURE NORTH OF THAT BIG FIELD IN NEW ZEALAND)

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Deepwater Taranaki contains up to 10 km of sediment. An early rift sequence is overlain by a large Late Cretaceous delta culminates with Rakopi Formation coal measures which mark the break-up unconformity following the start of Tasman Sea spreading. A passive margin succession follows as the New Zealand mini-continent gradually subsided, with sediments becoming gradually finer grained until carbonate deposition dominated during the Oligocene. Initiation of the present plate boundary about the start of the Miocene caused uplift and renewed clastic deposition in the form of spectacular channel and turbidite complexes.

The present reconnaissance seismic grid indicates at least six subtle Cretaceous structures that are large enough to contain a billion barrels of oil or several TCF of gas, suggesting that the first drilling targets may be Late Cretaceous fluvial and marine sands draped across gentle basement structures. Additionally, Cretaceous structures are commonly overlain by Miocene channel and turbidite sands that are also draped across underlying highs.

The similar, but much smaller structures of Tui, Amokura and Pateke, below the Taranaki shelf, are currently being developed by AWE. Future drilling will take discoveries closer to the shelf edge and ultimately the larger prises will be sought in deeper water.

PETROLEUM 2.1

Seismic Modelling and Inversion

SEISMIC PHYSICAL MODELLING OF RESERVOIRS – ITS PAST, PRESENT AND FUTURE

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In the early 1970s, conventional 2D seismic methods were used to understand subsurface geological structure. 3D surveying had not yet arrived as a method for delineating oil fields. Gulf Oil Research Laboratories was working on the problem of how to convince geologists that to delineate complex structure, seismic data should be recorded more closely spaced than was accepted practice.

A physical modelling system was constructed utilising a metre square water tank. Scaled models of geologic structures were suspended in the tank and an ultrasonic source and receiver pair was moved over the models to mimic both conventional 2D and experimental 3D seismic reflection surveys. 3D seismic migration algorithms were developed using the digitally recorded model data. The results clearly demonstrated the pitfalls of using widely spaced 2D seismic lines in the interpretation process – 3D acquisition and processing was required for accurate imaging.

Exxon was next to build a physical modelling system. When Gulf was taken over by Chevron, the Gulf modelling system was donated to and installed at the University of Houston, where a new laboratory housed a larger tank. Subsequently, other physical modelling systems were built in China, Japan, Australia, Saudi Arabia and Holland.

State-of-the-art recording has changed from single shot to single receiver, to multi-shots into 48 receivers, with further channel expansion soon. From simple impulsive shot recording simulating explosives, the technology has moved to simulation of any form of vibroseis sweep or frequency required. From simple plastic models, the technology has moved into the realm of injecting fluids into real sand reservoirs in pressure vessels.

MODELLING OF MULTIPLES IN 3D FOR ANY ACQUISITION GEOMETRY

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While constrains on source and receiver sampling for convolution SRME are easily fulfilled in the 2D case, the problem become significantly more complex in 3D. By requiring ideally equal and coincident source and receiver sampling for performing the surface consistent data auto-convolution required by the method, it constrains the acquisition geometry toward the denser possible designs.

For allowing the acquisition effort to be focused in illumination considerations related to imaging purposes instead of anti-multiples constrains, a series of processing solutions are now available, that made possible the use of 3D SRME methods for any kind of 3D acquisition geometries, including OBS (Ocean Bottom Surveys) and WATS (Wide Azimuth Towed Streamer) geometries.

Latest improvements on efficient interpolation methods, allied to larger storage and computing capacities, allow for the regularisation of irregularly sampled and aliased data toward regularly sampled grids suitable for the convolution based 3D SRME. It is a purely data based approach, free of any previous knowledge of the propagation velocity fields.

The alternative approach is the partial or full model based approach where wave equation modelling techniques are used for predicting 3D multiple models. The particularity of such approach is that its flexibility allow for handling any extreme acquisition geometry, as it can even apply to OBC geometries when no surface data is made available.

Although natural higher folds related to WATS geometries allow for better stacked or migrated sections even when not any anti-multiple is applied, 3D de-multiples are still needed for improving the data quality pre-stack. In this context, we can show that the state of the art of data-based and model-based 3D multiple modelling techniques allow for an efficient and accurate de-multiple processing.

NON-LINEAR JOINT AVO INVERSION OF PP AND PS WAVES IN A VTI MEDIUM

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In a stack of homogenous anisotropic layers, elastic properties and layer thickness are estimated using the seismic amplitudes from a pre stack gather. P-waves (PP) and converted shear waves (PS) are modelled using a convolution model in the frequency domain. Each layer is modelled with seismic properties such as Vp, Vs, density, the Thomson's anisotropic parameters (delta and epsilon) and thickness. For a source and receiver offset, travel-times, as a function of ray parameter, are calculated using Ursin and Stovas (2006) equations. A dynamic ray tracing algorithm implementing an iterative Newton's method was applied to travel-time equations to compute the ray parameter. In the interface of two layers Ruger (1996) equations for reflection and transmission coefficients were used to calculate effective reflectivity. A non-linear conjugate gradient (CG) algorithm was used to optimise a Ferobenius norm objective function. All the derivatives of the objective function with respect to each parameter model (layer properties) were calculated analytically and compared with numerical finite difference derivative. This results in stable derivatives and also reduces the extensive computation of finite differences. Because of non-linearity of the objective function and high dimensionality, CG needs to be carefully preconditioned. Non-linearity results mainly in complexity of model space (non-uniqueness) and low convergence. We implemented a covariance matrix of model parameters and data along with recursively scaling the step length to precondition minimisation. Thomson's anisotropic parameters estimated using joint PP and PS arrivals compare to those estimated using only PP are more accurate.

NEAR SURFACE 2

Environmental and Groundwater

FREQUENCY AND/OR TIME DOMAIN HEM SYSTEMS FOR DEFINING FLOODPLAIN PROCESSES LINKED TO THE SALINISATION ALONG THE MURRAY RIVER?

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Floodplains play an important role in catchment hydrology, representing a zone in which groundwater is shallow, and groundwater–atmosphere interactions through evapotranspiration (ET) are more pronounced. Modelling these systems can assist our understanding of which areas of vegetation are at high risk from salinisation in order to target them for management. Geophysical, particularly helicopter EM systems have the potential to provide detailed spatio-temporal information on the distribution of salinity in soils and groundwater, thereby assisting our understanding of floodplain processes. With this in mind, we examine the relative merits of high resolution helicopter electromagnetic systems for defining variations in groundwater quality and sediment salt load across the floodplain-highland interface along the Murray River floodplains of South Australia. In particular, we consider the relative performance of the RESOLVE frequency domain helicopter EM (FDHEM) and the SkyTEM time domain helicopter EM (TDHEM) systems. Results from two coincident surveys over part of the floodplain in the lower River Murray in South Australia are reviewed as are strategies for the inversion of the derived data. Results from fast approximate and layered earth inversons are compared in plan and section form. Both systems indicated the presence of an extensive flushed zone adjacent to the River Murray, but that this

zone is not always present. Both systems were useful in identifying finer scale variations between losing and gaining groundwater adjacent to the Murray River. Our results indicate that RESOLVE defines finer scale variations in the near surface sediments relative to SkyTEM, but in part, that is attributed to the latter operating in a dual mode and at a slightly higher survey altitude.

AN ASSESSMENT OF 'IN-STREAM' SURVEY TECHNIQUES ALONG THE MURRAY RIVER, AUSTRALIA

Michael Hatch[1]*, *Tim Munday*[2], *David Allen*[3], *Andrew Fitzpatrick*[4] *and Graham Heinson*[5]
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A number of tools have been developed to help hydrogeological investigators and managers understand the salinisation processes at work on the River Murray. Four techniques used to help investigators either directly measure the salt load entering the river or to image the distribution of conductivities under the river are evaluated in this study. These include Run-of-River surveys, in-stream towed NanoTEM, in-stream towed Resistivity, and Helicopter EM (specifically the RESOLVE FDHEM system). The study area is located in the Sunraysia region of Victoria and NSW. Each of the techniques examined has strengths and weaknesses related to its underlying theory of operation and mode of execution. Run-of-River samples the water salinity directly and then attempts to estimate river salt load and source location. It provides a direct measure of the salt entering the river but (a) only provides salt load information and (b) generally only provides information on a kilometre scale. The other three techniques are all geophysically based, and whilst they do not directly inform the investigator about salt loads in the river, they do provide information about conductivity distributions beneath the river, which then may be related directly to river salt loads. These geophysical methods sample the in-stream environment at three to 20 m intervals, and provide information from near the river surface to depths of between 10 and 40 m below the surface. This study presents results from a coincident set of surveys and for the first time, through their display as depth sections, and contoured depth slices their relative merits can be compared.

THE APPLICATION OF AIRBORNE GEOPHYSICAL DATA AS A MEANS OF BETTER UNDERSTANDING THE EFFICACY OF DISPOSAL BASINS ALONG THE MURRAY RIVER

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The pumping and disposal of saline groundwater from the margins of the River Murray in South Australia is an integral part of the Sate Government's salinity management strategy. It is specifically aimed at reducing groundwater levels and salt accession to the River Murray. Large volumes of saline water are typically disposed at the land surface in what are referred to as 'saline-disposal basins'. Although these disposal basins are now common, surprisingly little is known about their long-term efficacy or environmental effects. This study focuses on the analysis and interpretation of RESOLVE frequency domain electromagnetic data acquired over the Stockyard Plains saline-water disposal basins located southwest of Waikerie, South Australia, with a view to determining the extent of saline plume migration and improving our current understanding of the hydrodynamics of saline groundwater disposal in the area. The airborne EM data were calibrated using conductivity borehole data and statistical methods prior to modelling. Two sets of conductivity models were generated using conductivity-depth imaging and constrained layered earth inversion. The constrained inversion model provided information on the depth, thickness and presence or absence of aquitards, specifically the Blanchetown Clay, and map variations in groundwater conductivity in the region around the existing natural disposal basins. Conductivity depth imaging defined the extent and condition of the groundwater mound beneath the existing disposal basin. In addition these data can be used to investigate the potential for extending disposal options in the vicinity of the existing basin by identifying areas where aquitards (the Blanchetown Clay) are present or absent.

15:30–17:30

MINERALS 1.3

Case Histories

RISK MITIGATION THROUGH THE USE OF GEOPHYSICS

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There are three principal sources of risk in mining and exploration: the external market, process and mining risk and geological risk. Only the external risk is truly beyond the control of the owner/operator. Underlying all other risk is the quality of the understanding of the geological risk that underpins mining and processing decisions. A number of case studies are discussed which highlight areas where Anglo and affiliated companies have employed geophysics to reduce the geological risk in exploration, delineation and production.

Geological risk is intrinsically 3-dimensional in nature. Despite the fact that the parameters that describe a geological entity can generally be measured with some precision, e.g. density, grade, chemical composition and hardness, lack of access in the third dimension (depth) combined with cost means that we invariably deal with incomplete data sets. Yet it is precisely the geological model that informs the type and size of mine and processing options. The chances are that the resulting mine/process options will be sub-optimal and in the worst cases completely wrong.

Acquiring the necessary information costs money. Not having the information inculcates risk. There must be an optimum position where the overall cost of the information and the reduced risk is at a minimum. Traditional methods of exploration/delineation no longer suffice. A judicious mixture of traditional and geophysical methods offers an opportunity to gain an adequate understanding of the critical geological parameters and thereby make better decisions on mine/process design.

GEOPHYSICAL CHARACTERISTICS OF THE SOUTHERN COROMANDEL VOLCANIC ZONE AND ASSOCIATED EPITHERMAL DEPOSITS, NEW ZEALAND

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The Coromandel Volcanic Zone (CVZ) is part of a Miocene–Pliocene volcanic arc in the North Island of New Zealand and hosts the Hauraki Goldfield. In the southern part of the CVZ, about 15 epithermal deposits occur, located within Late Miocene–Pliocene andesite flows. Regional gravity data from the southern CVZ are dominated by steep linear gravity gradients which delineate the major fault which bounds the Hauraki Graben to the west, and other large faults associated with the Waihi trapdoor caldera in the east. Regional magnetic data are dominated by a large bi-polar anomaly, coincident with the Waihi Caldera, which may result from a sub-caldera intrusion; otherwise, high-amplitude shorter wavelength magnetic anomalies are characteristically associated with the volcanic rocks. The epithermal deposits exhibit gravity signatures with two contrasting modalities:

(i) small negative anomalies (e.g. ≤30 g.u. at Golden Cross and Scotia) and
(ii) small positive anomalies (e.g. 30–50 g.u. at Karangahake and Waihi-Favona).

Near-surface, low density clay-altered andesites can account for the small negative gravity anomalies. However, given the ubiquitous occurrence of such altered andesites, the positive gravity signatures indicate that significant mass anomalies must occur at greater depths which may be either dense intrusions and/or zones of concentrated sulfide mineralisation. High-resolution magnetic and radiometric data reveal distinctive signatures associated with the epithermal deposits; extensive magnetic quiet areas clearly delineate the location and extent of the hydrothermal alteration zones around the deposits and more localised zones of high potassium count within these magnetically quiet areas delineate potassium enrichment, indicative of potassic alteration.

THE IMPORTANCE OF GEOPHYSICS AND REMOTE SENSING IN ANGLO PLATINUM'S EXPLORATION EFFORT

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Anglo Platinum is the world's largest PGE producer and is currently exploring in several countries on various continents. Current exploration ranges from grassroots to near-mine expansions. Anglo Platinum uses an integrated exploration approach. Conventional geological exploration methods such as mapping and drilling are routinely supplemented with sophisticated geophysical and remote sensing data.

Geophysical wireline logging is a fundamental tool for determining the physical properties of the target and country rock. Knowledge of the physical properties is used to determine the optimum geophysical technique for subsequent exploration and ore body definition. The wireline logging is complemented by geotechnical borehole logging to provide data aiding rock stability assessments for future underground development or slope stability assessments for open pits.

A variety of airborne surveys have been flown over Anglo Platinum's concessions, amongst them high-resolution magnetics, EM surveys and gravity gradiometry. The magnetic surveys are the most significant for identifying disturbances. Consequently Anglo Platinum is a major participant in the Anglo Group Low-Temperature SQUID development project.

Prior to shaft sinking, risk reduction is undertaken using 3D seismic surveys. Survey design varies depending on the local geology and depth of the economic horizons. Surveys to date have vastly increased geological confidence.

Detailed satellite imagery is used for field-mapping. The availability of high resolution Quickbird and Ikonos imagery has assisted exploration in defining geological features.

After comprehensive data acquisition and verification all geological and geophysical datasets are integrated to produce a detailed 3D ore body model for mine planning.

INMINE GEOPHYSICS FOR MINE PLANNING

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This paper will provide case studies demonstrating how in-mine geophysics is now being routinely used in a number of mines in Western Australia to map mineralisation and structures ahead of mining. Refined equipment and procedures enable in-mine geophysics to be run in any drillhole or tunnel in an underground mine with minimal impact on the mining process. These geophysical techniques provide a much higher resolution than traditional exploration techniques, mapping interfaces to an accuracy of less than 1 m.

Two of these in-mine geophysical techniques are downhole electromagnetics and Borehole radar. Downhole electromagnetics is a proven geophysical technique that can be used to map planar conductive mineralised zones, for example massive sulfide. Borehole radar is a proven geophysical technique to map the topography or ore zones and structures that control mineralisation. Borehole radar can also be used in transmission mode to map breaks and offsets in ore ahead of mining.

PETROLEUM 1.3

Processing

INSTANTANEOUS ATTRIBUTES – THE WHAT AND THE HOW

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Since their introduction by Nigel Anstey and Tury Taner in the 1970s, attributes have become an integral tool in the interpreter's arsenal. At present, no direct relationships have been established between all attributes and physical and geological characteristics of the subsurface. Their discriminatory properties, however, allow very useful classifications to be performed. This paper deals with various attribute related issues.

Firstly, we consider the theoretical and physical aspects concerning instantaneous attributes, particularly instantaneous phase. This attribute is of central importance since it describes the location of events in the seismic trace and leads to the computation of other instantaneous quantities.

Secondly, we deal with the issue of information content. It has often been implied that attributes convey no more information than that present in the original seismic trace from which they are derived. This, however, is akin to claiming that David contains no more information than the raw marble from which Michael Angelo freed him. A seismic attribute section provides that much more information. The attribute in time attempts to enhance resolution, whereas the attribute property in the spatial dimension emphasises continuity. These important and interesting issues will be dealt with theoretically and by example.

Finally, we present and illustrate, by synthetic and real data examples, a novel, hybrid attribute which has been constructed to provide high resolution information. We must point out that, as is always the case, our attribute is dependent on the phase of the source wavelet.

We conclude the presentation with a look at the very recent local attribute formulation by Sergey Fomel, which we compare with our hybrid approach delineated in this paper.

APPLICATION OF FREQUENCY SPLIT STRUCTURALLY ORIENTED FILTERING TO SEISMIC WHITENING AND SEISMIC INVERSION WORKFLOWS

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This paper describes a new seismic processing method that uses dip-steered filtering to improve the performance of subsequent seismic whitening and relative impedance inversion. Given favourable acquisition and processing parameters, the availability of high frequency signals is ultimately limited by poor signal/noise ratio (S/N) at high frequencies. Managing this noise is key to accessing the high frequency information.

We show that although spatial filters applied to broadband seismic data mainly affect the central pass-band, a frequency splitting approach can specifically benefit the targeted high frequency parts of the spectrum. The dip-steered filters trade spatial resolution for increased S/N, but only in the frequency bands that are boosted during the whitening or inversion processes.

The S/N of the low frequencies can be improved using a similar process during acoustic impedance inversion. Applying the technique prior to full-bandwidth inversion allows the use of lower seismic frequencies, and reduces reliance on a pre-existing background model.

We can apply frequency split dip-steered filtering to pre-stack common offset volumes in a similar fashion. This delivers frequency balanced gathers with lower noise and increased resolution, ultimately leading to improved residual moveout correction, reduction of offset dependent tuning, and improved elastic inversion products.

Independent well ties demonstrate the validity of the technique and are used to QC the products.

The value of increased resolution in the seismic data volumes is illustrated with several case histories from different surveys and reservoirs.

DETAILED REFRACTION STATICS WITH THE GRM & RCS

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Statics are the corrections to seismic reflection data for the weathered layer and variable topography. Traditional statics routines estimate an initial model of the weathering and then iteratively refine it with NMO velocity analyses and residual statics routines. However, this approach is inefficient, especially with the very large volumes of data characteristic of single sensor data, and it has not proven to be especially efficacious with S-wave statics.

By contrast, a new approach using the GRM and the RCS obtains an accurate time model of the weathering which does not require substantial improvement with residual statics. Accuracies of ±1 millisecond are routinely achieved. As a result, the new GRM-RCS approach can improve the efficiency of normal data processing through eliminating at least one iteration of velocity analyses and residual statics.

There are up to five stages with the GRM-RCS approach. Starting with a new 1D QC algorithm, each stage provides greater resolution of the time model than that obtained in the previous stage. In the final stage, the surface consistent time delays in the surface soil layers are separated from the non-surface consistent time delays originating at the base of the weathering. The corrections for the surface soil layers are necessary for wave equation re-datuming and for digital group forming with single sensor data.

The GRM-RCS method is effective with data in which cycle skipping occurs. The RCS generated with 3C single sensor data can provide a detailed S wave time model of the weathered layer.

APPLICATIONS OF TIME DOMAIN HIGH-RESOLUTION RADON DEMULTIPLE

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The standard method to compute the parabolic Radon transform to demultiple used to be the frequency domain least-squares (LS) approach. In recent years the high-resolution (HR) Radon transform has become popular. The HR transform is based on the standard LS frequency domain Radon transform, but uses an alternative stabilisation method, which can yield higher

resolution in the curvature direction in the Radon domain. Improved resolution can lead to better aliasing protection and improved amplitude preservation and demultiple efficiency. Unfortunately, while the frequency domain HR methods can give very good results on simple data, for more complex data the advantages compared with the LS approach are often reduced.

Time domain HR Radon demultiple is not new, but (probably due to relatively high computation costs) is not commonly used. A time domain HR Radon transform improves the resolution in the Radon domain both in the curvature and zero-offset-intercept time directions. Consequently higher resolution can be obtained, in particular for complex data with events with many different curvatures. Although one would expect the improved resolution to yield better multiple elimination, not many examples of the actual multiple elimination are given in literature, in particular for field data. In this paper the effect of the improved resolution is studied on synthetic and field data, and it is shown that particularly for more complex data, the time domain HR Radon transform can provide much improved demultiple efficiency, aliasing protection and primary preservation, compared with the frequency domain HR Radon transform.

PETROLEUM 2.2

Seismic Modelling and Inversion

THE VIRTUAL SOURCE METHOD – VERIFYING THE CONCEPT USING PHYSICAL AND NUMERICAL MODELLING

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Rapid velocity variations in the near surface cause strong scattering that severely distorts and disperses wavefronts, propagating both downward to reflectors and returning upward to receivers. The Virtual Source method is a new seismic reflection concept designed to image through the most complex, heterogeneous part of the overburden, without the need of an overburden velocity model. The method involves the use of surface shots with down-hole receivers below the most complex part of the overburden. Cross-correlation is used to create a downward continued dataset with virtual sources at the down-hole receiver locations. This paper tests the concept using a synthetic and physical model, both exhibiting extreme heterogeneity in the near surface. The paper shows that a highly complex overburden is actually beneficial to the virtual source method, due to the wider radiation patterns that result from the virtual sources at the subsurface receiver locations.

MULTI-COMPONENT SEISMIC-RESOLUTION ANALYSIS USING FINITE-DIFFERENCE ACQUISITION MODELLING

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A number of simple rules-of-thumb have been widely used to predict vertical and horizontal resolution limits (e.g. Rayleigh and Widess limits; Fresnel zone). These measures provide a basic feel for the relationship between final image-wavelength and resolution. However, seismic resolution ultimately depends on more fundamental factors. These include survey design (fold, receiver spacing, aperture, etc), source bandwidth, geology, and the design and sequence of algorithms used in the CMP stacking process. As targets become more subtle, resolution analysis needs to be more controllable in terms of these individual factors.

For this investigation we use viscoelastic finite-difference modelling to simulate the acquisition of a sequence of multi-component shot records over 2D geological models of arbitrary complexity. These shot records are then processed and interpreted using standard real-data methods. This allows us to examine the influence different processing algorithms have on resolution.

Attenuation (Q) is specified throughout each model for P-waves and S-waves independently. This facilitates an instructive comparison of the resolution capabilities of conventional and converted-wave images.

In this paper we demonstrate resolution issues for representative petroleum and coal scale models, including stratigraphic lenses and coal barren-zones. These examples illustrate conventional P-wave resolution capabilities, and also clarify why converted-wave imagery tends to be more competitive, in terms of resolution, in the coal context than in the petroleum context.

Realistic numerical modelling, simulating the full acquisition sequence, leads to a more pragmatic understanding of seismic resolution issues. It is a valuable tool, both for survey planning and image interpretation.

SOME SEISMIC EXPERIMENTS ON SUPERCRITICAL CO_2

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When CO_2 is injected into a formation in its supercritical form, it acts as a gas having the ability to be compressed to a much lower volume than in its liquid form. During the Naoka site injection in Japan, CO_2 was injected in its supercritical form into a saline aquifer and a cross-well tomography experiment was performed in which a seismic source was placed in one well and receivers in another. The objective of the cross-well tomography was to image the CO_2 during injection, in order to track the progress of the CO_2.

In order to simulate this field experiment, we used a large synthetic sandstone core representing a physical model of the reservoir. The water-filled core was subjected to a confining pressure of 8.5 MPa, with a pore pressure of 8.2 MPa, and had ultrasonic transducers placed down opposite sides of the core. The hope was that as the supercritical CO_2 passed through the core, the seismic system would record a seismic tomogram, a reflection tomogram and the seismic transmission response as the supercritical CO_2/water interface moved through the core.

This paper presents the development of the experiment to simulate the field response, and the results so far of the injection process. There was a velocity change of some 5% when supercritical gas replaced water, but there was also a major amplitude change with some 25% reduction in transmission amplitude when

supercritical CO_2 replaced water. This has consequences for monitoring the state of phase of CO_2 during injection, using seismic data.

INSIGHTS INTO SEISMIC INVERSION FOR GEOTECHNICAL PROPERTY ESTIMATION IN COAL MINING

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Most geotechnical information used in coal mining is obtained from core drilling, geophysical logging and underground mapping. This information, however, is discontinuous and techniques that could provide continuous data over three-dimensions would be of considerable use. Such an additional source of geotechnical information lies with inverted 3D seismic reflection data. Seismic inversion provides acoustic impedances, the product of density and velocity and from these it is possible to estimate basic geotechnical information.

While seismic inversion is relatively robust when tracking lateral variations in lithology or rock composition, it is intrinsically non-unique because band-limited seismic signals do not carry all of the information necessary to describe the complexity of the actual geology. Selection of one solution from the many potential candidates is required. Consequently integrating borehole logging data with seismic data is very important. In addition, analysis of the geophysical logs allows the geotechnical properties of the rock layers to be determined through the Geophysical Strata Rating (GSR), a parameter more familiar to geotechnical engineers. This in turn allows us to convert the seismic inverted acoustic impedance to GSR through well tie and log-seismic correlation.

In this paper, we analyse the effects of initial constrains on inverted impedance. We will use 3D seismic surveys in the Bowen Basin coalfields of Queensland to illustrate our approach.

NEAR SURFACE 3

Contaminated Sites

ON THE ADVANTAGE OF B-FIELD SENSOR ARRAYS IN TEM: FROM MINERALS TO UXO AND BACK AGAIN

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EM receiver systems, which measure magnetic field (B-field detectors), not time rate of change of magnetic field, are in frequent use in mineral exploration, and are subject of a current development for detection of unexploded munitions. The advantages of B-field detectors stem from both logistical and target discrimination capabilities. This paper quantifies the advantages of the B-field measurement using simple mathematical models for the response of highly conductive mineral targets in a conducting earth, and for unexploded large-calibre steel munitions in the presence of scrap metal.

The small size of B-field detectors greatly facilitates the use of arrays of sensors. A series of model studies was conducted to establish what improvement in target orientation/shape information could be achieved with single or multiple B-field sensors compared with conventional moving-loop surveys conducted using single-component single-sensor in-loop systems.

The model studies show use of a single vector sensor delivers an order of magnitude greater accuracy in location in 3D space and orientation of the target, compared with the use of vertical-component only data, but both sensors are likely to produce unstable orientation/shape estimates. Use of an array of three vector sensors has the advantage of delivering accurate and stable estimates of both location and orientation/shape of the target.

These finding are currently being implemented in a new design of metal detector designed for location and discrimination of unexploded munitions. The results are equally applicable to the design of multiple-receiver arrays for moving-loop EM surveys in mineral exploration.

INTERPRETATION OF HIGH-RESOLUTION LOW-ALTITUDE HELICOPTER MAGNETOMETER SURVEYS OVER SITES CONTAMINATED WITH UNEXPLODED ORDNANCE

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Throughout the world, millions of acres of potentially productive land are contaminated with unexploded ordnance either due to past-conflicts or to military training. Low-level helicopter magnetometry (Helimag) is currently being used to rapidly cover large areas and identify regions that are potentially clear of hazardous munitions. The configuration we currently use comprises 7 cesium vapour magnetometers, horizontally spaced 1.5 meters apart on a boom several meters in front-of the helicopter. Magnetometer data are collected at 100 Hz at altitudes as low as 1.5 m above the ground along transects spaced 7 m apart. From this dense, high-resolution data, potential metallic targets as small as an 81 mm mortar are identified using a combination of manual and automatic picking methods. The target picks are then used to estimate densities of potential contamination. In this talk we will focus on some of the technical challenges involved with interpreting large volumes of Helimag data. These include variations in sensor height between adjacent swaths, potentially large magnetic features in the data due to geology and overlapping target signatures from closely spaced anomalies. We will discuss the types of quantitative information that can be extracted from the data, such as estimated object size, along with some of the fundamental limitations of quantitative interpretation. Lastly, we will describe potential applications of the system to mineral exploration through its ability to rapidly collect high-density, low-altitude magnetometer data over large areas.

DETECTABILITY BY ELECTROMAGNETIC DEPTH SOUNDING – A DATA MINING TOOL AIDING INTERPRETATION OF SHALLOW SEDIMENTS, ALTERED BY OIL AND GAS SEEPS

Shastri L Nimmagdda[1]*, *Heinz Dreher*[2] *and Kalyan Chakraborty*[1]
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Electromagnetic depth sounding (EMDS) data are computed for simulated multi-layer earth models at different frequencies and geometries, using digital linear filters. Detectability of sub-surface layers is computed as point-to-point difference of data instances between three-layer–homogeneous layer and two-layer–homogeneous layer media for similar range of frequencies. H and K-type earth models are also considered in the computations. Response curves, computed for two different layer earth media models, are superimposed, thus, the separation between curves is the direct indication of the involved 'detectability effect'. The degree of separation among response curves between two geometrically or parametrically changing data properties, called resolution, has direct impact on detectability effect.

Though detectability does not provide any qualitative or quantitative interpretation of data attributes, but computed detectability effect significantly changes EMDS response resolution at varying layer–earth data attributes. Knowledge on strength of detectability and scalable properties among layer–earth media are interpreted based on resolution and coherency between two model response curves. Because of change in layered earth properties, varying horizontal and vertical resolution and coherency attributes between response curves, provide considerable detectability effect. This process, termed as data-mining, facilitates extraction of knowledge of layer properties within multi-layer earth media. This detectability effect provides knowledge of n-layer–earth simulation, which can effectively respond to and aid the interpretation of actual geological models, deduced from experimental data. These studies could prove to be useful for investigating shallow petroleum oil and gas seeps and their associated sediment alterations in the basin margin areas.

ELECTROOSMOSIS IP EFFECT AS AN INDICATOR OF HYDROCARBON COMPOUNDS' CONTAMINATION: A FEW CASE STUDIES

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Petrochemical plants and airports may have subsurface pollution plumes caused by spilled hydrocarbons. The method of TDEM soundings was successfully used for the detection and delineation of hydrocarbon contamination in groundwater in a few areas of Russia and South Africa. There are two principal indicators for the presence of hydrocarbons in groundwater: an increase in electrical resistivity in the groundwater saturated layer, and an IP effect of the electro-osmosis type. This effect is superimposed on time domain electro-magnetic (TDEM) and distorts the TDEM signals. It was shown than the electroosmosis polarisability η is the ratio of surplus electrical conductance to the electrical conductance in a pore space. The value of the decay constant τ is controlled mainly by the radii of pores. Theoretically, the process of an IP effect of the electro-osmosis type can occur in different types of sediments. In reality, however, an IP-effect can only be recorded by TDEM in water-saturated sediments with an imperfect relationship between the three phases if the size of pores is in the range $1 \cdot 10^{-5} - n \cdot 10^{-4}$ m.

The interpretation had been carried out using St version as an indicator of the IP effect, and mathematical modelling provided forward calculation of the electromagnetic field in multilayered polarisable media. Follow-up drilling results confirmed that the contaminant plume could be mapped by identifying the IP effects on the individual soundings. However, not all soundings that predicted the presence of HC were correct (only about 70%) and further studies are undertaken to isolate the cause of IP effects that mimic the HC polarisation effect.

Day 2: Tuesday 20 November 2007

08:30–10:00

MINERALS 1.4

Seismic

SEISMIC REFLECTION SURVEYS TO ASSIST NICKEL AND GOLD EXPLORATION IN THE WA GOLDFIELDS

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In August 2006 pilot high resolution 2D seismic surveys were carried out in the Hunt-Beta-Intrepide area near Kambalda in WA to provide a 'proof-of-concept' for the use of surface reflection surveys for guiding exploration for nickel sulfide and gold in this area.

Specific objectives for these surveys were:

- Verify that seismic reflection can accurately and reliably map the ultramafic-Lunnon Basalt contact (which is prospective for nickel).
- Improve resolution of coherent reflectors in the top 500 m of the seismic section compared to previous more regional surveys.

Assess the effect on resolution of seismic data of different seismic sources (explosives, vibroseis, weight-drop), line orientation, and different recording specifications.

The pilot survey demonstrated:

1. The basalt ultramafic boundary is usually a good reflector.
2. The resolution within the top 500 m using explosive sources was a factor of 2 better than previous surveys with a Vibroseis source.
3. The resolution of the weight drop source was similar to but slightly better than the Vibroseis source. Line direction did not appear to have a strong impact on data quality.

In addition:

- A correlation was noted between bright spots (i.e. zones of strong reflectivity) and Ni sulfide ore shoots.
- The survey mapped a number of faults/shears which should assist in the overall understanding of the geology.
- Intrusive porphyries appeared as zones of reduced reflection on the seismic image.

DETAILED 2D & 3D SEISMIC REFRACTION SURVEYS AT MT BULGA

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Detailed 2D and 3D seismic refraction surveys were carried out at Mt Bulga. The Mt Bulga ore body, which is located near Orange in south-eastern Australia, consists of a narrow (5–10 m) syngenetic fine grained banded massive pyrite–galena–sphalerite–chalcopyrite in steeply dipping unfolded Silurian altered metasediments.

The 2D seismic refraction profile was recorded with a station separation of 2.5 m, across a small ridge, which also marks the approximate location of the massive sulfide ore body. The data were processed with wave eikonal refraction tomography using a starting model generated with the 1D tau-p inversion algorithm and with the Generalised Reciprocal Method 'Statics' Smoothing Method (GRM SSM). The 1D tau-p refraction tomogram showed that the ore body has a higher seismic velocity than the adjacent regions, whereas the GRM SSM showed a low seismic velocity in the ore body. A density model, which was generated with the head wave amplitudes and the refractor velocities, showed a marked increase over the ore body, suggesting that the lower seismic velocity in the ore body is more likely. These results demonstrate that seismic refraction profiles can provide useful information on depths of weathering and density contrasts for joint inversion with either airborne or ground gravity data.

The 3D seismic refraction survey was conducted over a major shear zone near the ore body. Although the shear zone is nominally a 2D structure, the 3D seismic refraction results show a cross-cutting fault orthogonal to the shear zone, and azimuthal variations in rock fabric, not detected on an earlier 2D traverse.

PROCESSING AND SEISMIC INVERSION OF THE INTREPID SEISMIC LINE AT THE ST IVES GOLD CAMP, WESTERN AUSTRALIA

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The use of seismic methods in mineral exploration has increased in recent years in Western Australia. However, unlike sedimentary environments, seismic exploration in hard-rock environments is cumbersome. Difficulties commence with data acquisition in relation to mine-site locations, restrictions and inaccessibility resulting from seismic lines being not aligned with dominant structures. The regolith and weathered material up to 150 m thick, scatter seismic energy and produce variable time delays (static corrections) that could exceed 200 m in some areas. Complex structures such as dyke intrusions, severe faulting and folding offer further challenges to the application of seismic methodologies. Lack of deep boreholes and limited availability of sonic logging make interpretation of seismic data still more difficult.

Each of the above issues has a systematic solution that begins with understanding the requirements of the final stage in analysis of the seismic data. The final stages of inversion and multi-attribute analysis require accurate structural image and consistent amplitude and phase information from the seismic responses. Accurate structural imaging is often difficult to achieve because of the regolith issues and unfavourable line-orientation with respect to the underground structures. Low signal-to-noise ratio, high ambient and source-generated noise and variable source and receiver coupling present serious challenges for preservation of true amplitudes. However, before any of these obstacles are addressed classifying relationships between seismic attributes and various rock types that are likely to host specific minerals are necessary. For that purpose an extensive 'seismic response data base' needs to be derived from log measurements, core sample tests, and *in situ* geological knowledge.

MINERALS 2.1

Modelling/Inversion

PRACTICAL 3D EM INVERSION – THE P223F SOFTWARE SUITE

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Over the past 27 years, the AMIRA P223 project series has produced an extensive body of EM modelling and inversion programs for use by industry for planning and interpreting surveys and for the development of new EM exploration instruments. The earth models for both modelling and inversion include a very general full domain 3D finite elements (Loki class), 3D compact finite-elements (Samaya class), 2.5D full-domain finite-elements (Arjuna class), 3D multiple plates in the basement of a multi-layered host (Leroi class) and a 1D layered earth. The programs can be used for any frequency or time-domain AEM system. For ground and downhole systems, sources can include multi-vertex closed and open (grounded) loops, magnetic dipoles and plane waves. Receiver types are magnetic dipoles, electric dipoles and single point electric fields. Survey types include fixed source with independent surface or downhole receiver lines, moving source with multiple fixed-offset receivers and magnetotellurics.

The P223 project series has concluded. Previously the software generated by these projects has been available only to the project sponsors and their designated contractors. From September 2007, all programs are commercially available to anyone through the Maxwell EM environment. From January 2010, the entire suite including Fortran 90 source code will be

open source. The purpose of this paper is to make the wider exploration community aware of the capabilities offered by this extensive software suite.

PRACTICAL 3D EM INVERSION

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The goal of electromagnetic (EM) inversion for mineral exploration has long been to recover 3D models with high conductivity contrasts, heterogeneous hosts and arbitrary geometric complexity such as topography and unconforming interfaces, for any type of EM system. In the work presented here, this is achieved using a 3D full-domain edge-element finite-element method which enables the accurate modelling of arbitrarily complex 3D models with conductivity contrasts up to $10^6:1$. Inversion is based on the iterative Gauss–Newton method, which is solved using either SVD or model norm regularisation. The accurate and efficient computation of the sensitivities is critical to the practicality of the software. We introduce the domain differentiation method for this purpose, and compare its results to those obtained using the adjoint operator method. Mineral exploration case studies are presented for the inversion of ground and airborne EM data. The integration of these results for interpreting 3D geological structure is also discussed.

SPATIALLY CONSTRAINED INVERSION FOR QUASI 3D MODELLING OF AEM DATA

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The spatially constrained inversion (SCI) is a robust methodology for quasi-3D modelling of geoelectrical and EM data of varying spatial density, using a 1D forward solution. It can be implemented with airborne or ground-based data, both in frequency and time domain. The SkyTEM data here presented show how the SCI produces laterally smooth results with sharp layer boundaries that respect the 3D geological variations of layered settings. Paleo-channels structures are accurately imaged. Information migrates horizontally through spatial constraints applied between nearest neighbouring soundings, and enables the resolution of layers that would be locally poorly resolved. The constraints are built using the Delaunay triangulation, which ensures automatic adaptation to data density variations. Data sets, models and spatial constraints are inverted as one system, producing layered sections with smooth horizontal variations. The SCI suppresses the elongated artifact commonly seen in horizontal maps (i.e. average resistivity, or saltwater boundary elevation maps) resulting from profile oriented data sets. Being an over-determined parameterised inversion problem, it produces a full sensitivity analysis of the output models, an essential tool for the evaluation of the results.

PETROLEUM 1.4

Reservoir Characterisation

FRACTURE CHARACTERISATION OF THE ELK CARBONATE RESERVOIR, PAPUA NEW GUINEA

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The Elk trend gas field is situated in a frontal location of the Papua New Guinea Fold Belt. The Elk reservoir is hosted in the Miocene ramp to deepwater Puri Limestone and Eocene to Oligocene shelfal Mendi Limestone. FMI analysis from the Elk-1 well has constrained the *in-situ* orientation and distribution of fractures, and provides some indication of fracture aperture, but information is constrained to the wellbore. Offset well FMI, structural core analysis, and outcrop studies provide information on fracture morphology, generating mechanisms and spacing in analogous limestone to parts of the Elk gas reservoir but not within the reservoir itself. The permeability demonstrated by the Elk-1 well from DST-1 and DST-2 was extreme and can only be explained by a significant well connected natural fracture network in the relatively tight section penetrated. These DST's and a DST in the Bwata fractured carbonate gas reservoir, in the same tight Puri Limestone as the upper Elk reservoir provide some indication of maximum fracture storage and interconnectivity. Within the Elk reservoir, fractures were divided into producing and non-producing during wireline logging based upon detailed analysis of wellbore temperature, fracture location, orientation and morphology. Only a fraction of the fractures flowed gas during logging but these have facilitated interpretation of the geometry and interconnectivity of the fracture network outside the wellbore.

FAST TRACK RESERVOIR CHARACTERISATION OF A SUBTLE PALEOCENE DEEP MARINE TURBIDITE FIELD USING A ROCK PHYSICS AND SEISMIC MODELLING LED WORKFLOW

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The Brenda Field in UK North Sea Block 15/25b has undergone very rapid exploration and appraisal in 2004 and is now poised to move into the production phases over the next 12 months.

Over 12 'cluster' penetrations of the Palaeocene Upper Balmoral sandstone reservoir have been drilled and a substantial amount of reservoir data has been collected. The objectives of the project required fast assimilation and integration of rock physics and inversion into operations to ensure that each well was targeted and optimally drilled with the benefit of the enhanced understanding of the previous data collected – in practice this involved making 2–3 well prognoses for non vertical wells ahead of drilling.

We describe the combination of rock physics driven seismic interpretation of attributes, and a new technology for 'inversion of

inversion' for reservoir characterisation used to fast track the Brenda field previously considered non economic.

The Brenda net oil reservoir varies from 10 to 30 m in thickness with 32API oil with low GOR oil trapped by a combination of structural and stratigraphic elements. The understanding of the relative importance of the two major controls and modifiers such as hydrostatic gradients is still evolving.

EXTRACTING SUBSURFACE INFORMATION FROM SEISMIC AMPLITUDES: PROMISE AND REALITY

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Over the last 30 years, the quality and usefulness of information derived from both pre-stack and poststack seismic amplitudes has led to increases in exploration success rates as well as to more effective use of amplitudes to predict reservoir properties away from well control. However, the temporal and spatial resolution and the signal to noise ratio of various attributes even for relatively shallow target depths are often inadequate to address subsurface issues of interest. An ongoing challenge to geophysicists is that of acquiring, processing and analysing surface seismic amplitudes so as to improve resolution and further quantify geological properties such as porosity, lithology and fluid types.

Seismic acquisition, processing and analysis technologies have advanced on many fronts. However, very little has been done to adequately compensate for the effects of wave propagation from recording surface to subsurface targets of interest. In fact processing models are typically devoid of the earth property detail required to compensate for scattering, illumination and attenuation effects. Analysis of various amplitude attributes taken from walkaway VSPs and modelling studies strongly indicate that the angle dependent transmission effects of shallow layers imposes a dominant imprint on reflected amplitudes. In many cases this imprint completely obscures subsurface amplitude variations that are required to determine subsurface properties of interest.

Finite difference models of layered earth transmitted and reflected pulses have led to the understanding that weak earth lenses and wide angle scattering can have first order effects on the relative phase, time and scale of angle dependent reflections which can lead to very large errors in inverted amplitude attributes.

Post-imaging, pre-inversion amplitude processing sequences can improve inverted amplitude attribute quality. Such software relies on statistical information drawn from well log and borehole data to constrain processed amplitude behavior to conform to that expected of bandlimited earth reflectivity.

FESAUS 1

Formation Evaluation and Geology

GRAND CHALLENGES IN FORMATION EVALUATION

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Breakthroughs happen in fields where the experts may not be expecting them. But the smart money is attracted to those who both know what the needs are and can recognise applications that can meet those needs. Where are the next breakthroughs going to come from? The answer to this lies in the question: What are the real needs of the industry?

We generally think of the reservoir engineer as the final user of our data and analysis, and to a large extent this is true. Reservoir engineers need information on porosity and permeability in almost all cases, and they need information on mechanical properties and chemically reactive properties in many cases. Geologists and geophysicists also need data from petrophysics, and these are often not the same data as the reservoir engineers need. Is there a way to find a more-universal method of formation evaluation that will yield results that are useful to all such clients?

The challenges the industry faces consist mostly of finding methods to obtain answers more quickly, more reliably, more directly, and more accurately. While incremental improvements in well-logging technology are necessary and ongoing, some revolutionary changes are likely due, and a 'paradigm shift' may occur during our careers. Some possibilities for a change in business-as-usual may include direct sampling of rocks, through slim-hole drilling with continuous coring or extensive sampling of cuttings and their analysis for macroscopic properties; new borehole analysis techniques that would become available through fibre-optic wirelines; and advanced probabilistic approaches using limited data.

INTEGRATION OF CONVENTIONAL PETROPHYSICAL INTERPRETATION AND BOREHOLE IMAGES

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Crocker Data Processing has worked on improving net to gross and volumetric computations in thin bed reservoirs and has an innovative approach that combines borehole image data and conventional openhole data. A particular problem with openhole image data is the imposition of its character on conventional resolution data produces an answer that whilst close, does not honor the resolution of the conventional data. The approach adopted by Crocker Data Processing involves independent computation of the resistivity, total or effective porosity and Vclay directly from image data and calibrating these results against openhole data. The results produce both independent Imagelog based petrophysical volumes as well as input that is high resolution and can be used in a deterministic petrophysical model. This resolution improvement allows heterogeneous thin bed reservoirs to have better volumetric parameters produced for incorporation in reservoir modelling and reserves calculation.

CLUSTER ANALYSIS APPLIED TO AN EXPLORATION DATASET: FACIES CLASSIFICATION FOR IMPROVED PROSPECT RISKING

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Prospect risking in a basin with scarce reservoir relies upon seismic attribute analysis and stratigraphic prediction. Petrophysics plays a fundamental role in this exploration workflow with acoustic logs

providing seismic calibration and rock samples and logs providing input to stratigraphic models.

This paper presents a petrophysical workflow centred on log cluster analysis in GEOLOG's FACIMAGE module. Facies are classes with constant and distinct character – effectively building blocks for up-scaling from rock-scale (petrofacies), to log-scale (electrofacies), to seismic-scale (seismic facies).

Over 100 SWS from fourteen exploration wells are classified into six petrofacies based on composition, grain size and fabric. Petrofacies are used to determine diagnostic logs for input to FACIMAGE and to quality control the final product. Unconstrained cluster analysis of well logs is performed in Geolog resulting in four electrofacies classes.

Six practical rules for cluster analysis emerge during the project and are presented. They cover best practices in the handling of input logs to ensure optimal results. Cluster analysis outputs are heavily dependent on the inputs and if used as a black box, misleading results easily occur.

Complications inherent to most exploration datasets are encountered including varying pore pressure, compaction state, fluid-fill, salinity and age. These challenges are overcome before meaningful clustering results are obtained.

Electrofacies classes are found to clearly distinguish silty turbidite mudstones from background claystones and so aid the utility of well logs in stratigraphic interpretation. Acoustic logs plotted by electrofacies show strong rock property trends (e.g. porosity-stress, Vp-Vs) so improving seismic calibration.

NEAR SURFACE 4

Regolith

REGOLITH GEOPHYSICS: RETROSPECT AND PROSPECT

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Australia leads the world in developing an understanding of the nature of regolith and regolith forming processes. This understanding is fundamental to the effective exploration of regolith dominated terrains and the effective management of our environment.

Geophysical techniques have an important role to play in characterising regolith materials, mapping their distribution, and mapping and monitoring regolith forming processes. The efficacy of these techniques, including processing and interpretation strategies, has improved dramatically in the last decade. New, large data acquisition programs funded by the federal government and focused on the regolith should act as an impetus for further improvements in these techniques.

This presentation reviews advances in geophysics over the past decade and considers the challenges and opportunities that will face regolith geophysicists in the coming decade.

STUDY OF GROUNDWATER FLOW IN SEDIMENTS AND REGOLITH DEFINED BY AIRBORNE GEOPHYSICAL SURVEYS

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An airborne electromagnetic survey flown around the wetlands north of Esperance was interpreted to assist in defining the groundwater conditions within the surrounding sediments and regolith of the floodplain and its influence on the wetlands.

The study shows the Esperance Floodplain is underlain by sediments of Eocene age deposited in near coastal marine conditions onto an undulating basement. Werillup Formation which is the deeper unit is often composed of permeable free flowing sands containing highly saline water which may be under artesian pressure. Deep drainage paths were interpreted wherever Werillup Formation was inferred. The Werillup is overlain by an aquitard of more clay-rich sediment which marks the boundary with the Pallinup Siltstone.

In the western part of the study area the study showed that whereas surface water flow is directed towards the fresher Lake warden deeper more saline water flows towards Pink Lake or the ocean. In the eastern part of the catchment, the EM data indicates a deep palaeochannel joining the Neridup area with the sea. This is probably part of the southern extension of the Cowan-Lefory Palaeochannel system.

10:30–12:00

MINERALS 1.5

Radiometrics

URANIUM OCCURRENCES ON GEOPHYSICAL IMAGES

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Known uranium mineralisations in the Northern Territory are revisited using the NT-wide geophysical datasets of the Northern Territory Geological Survey. Without introducing any physical variation of technique, modern imaging techniques are applied to show correlations in the vicinity of each of the known deposits. Three hypotheses which might extend the area of prospectivity – Kambolgie, Kalkarindji, and Bitter Springs associations – are tested against the images. The presentation is likely to be of value to explorers who have studied Northern Territory uranium deposits but are not skilled with image processing technology.

RADON EMANOMETRY IN URANIUM EXPLORATION USING ACTIVATED CHARCOAL: NAMIBIAN CASE STUDIES

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In this study the implementation and refinement of the Radon-on-Activated-Charcoal (ROAC) technique, developed by the South

African Atomic Energy Corporation in the 1970s, is discussed. Case study results are presented from two areas in Namibia.

Radon, contained in ground air, migrates to surface as a result of the pumping action of diurnal pressure variations. It is adsorbed onto activated charcoal contained in a cartridge, fitted into the base of an inverted cup and buried in the ground. The technique (here termed *RadonX*) differs from alpha-sensitive systems in that it measures gamma radiation arising from the ^{214}Bi and ^{214}Pb daughter products of the adsorbed radon. Thoron (^{220}Rn), arising from thorium that may be present, is not measured due to its very short half-life. The case study data are derived from an orientation survey over a known buried palaeo-channel of duricrust-hosted uranium, and from an exploration area potentially hosting uraniferous granites at depth. The *RadonX* surveys show:

- Improved sensitivity compared to a previous alpha-detection survey.
- Good repeatability. Some loss of sensitivity, due to possible large temperature variations between initial and fill-in surveys, is easily corrected for by repeat measurements.
- Improved resolution with detailed grids, allowing accurate mapping of uranium mineralisation and positioning of boreholes.
- Excellent penetration through residual or transported surficial cover. Given favourable porosity conditions, a depth of penetration of 80 m or more has been achieved.

Deployment is rapid and cost effective.

INTEGRATION OF BOREHOLE GEOPHYSICAL DATA IN 2D AND 3D TO DEVELOP A HAZARD INDEX

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A borehole hazard index is the integration of interpreted risk indexes with an existing geological and structural 3D mine or exploration model. Individual risk indexes are produced and combined with the purpose of providing a clear visual and quantitative method for determining varying degrees of risk associated with development through a particular geological rock volume.

Disparate data sets are used to characterise separate risk indexes established from user defined criteria. Input data sets include geological and structural logs and mine layouts, complemented by a borehole geophysical suite including borehole radar, optical and acoustic televiewers, density, neutron, resistivity, flowmeter and full wave form sonic.

The user defined criteria are established for individual project requirements and can include factors such as the intersection of structures, the presence of water ingress, proximity to structures with specific orientations and the presence of lithological units prone to failure.

The requirements of the integration environment vary; certain criteria can be adequately assessed in a 2D environment while other hazard indexes require data to exist in a true topological 3D environment where spatial queries can be performed.

The applications of a borehole hazard index include shaft site evaluations, and shaft sinking development planning. Additionally a hazard index can serve as a mine production tool, evaluating hazards in front of the face which will affect both safety and production rates. Successful deployment requires regular and timely update of the local structural model which can be achieved by automating the hazard index generation once the starting model has been defined.

MINERALS 2.2

Modelling/Inversion

INVERSION AND FORWARD MODELLING OF EM INDUCTION IN FOLDED SHEET CONDUCTORS: THEORY AND PRACTICE

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Application of the Integral Equation (IE) method to calculate the electromagnetic induction (EM) in multiply folded sheet conductors is simplified by replacing the conductor with trial source currents (two dimensional polynomials) of unknown amplitude. Using the Galerkin method to solve the IE, reduces the problem to inverting for the amplitudes of current basis (trial) functions. This results in the calculation of two matrices. One, the resistance matrix, is only a function of the sheet's dimensions and its conductivity. The inductance matrix is related to the self and mutual inductance of the trial currents, a function of sheet's geometry, and a vector describing the interaction of the primary magnetic field with each trial function. In comparing the solution for a flat sheet conductor, the folded conductor solution involves changes to the inductance matrix.

Forward modelling the EM response normally requires less than one second of CPU time using current computing units. Including this forward model solution in an inversion scheme to produce the parameters of multiply folded sheet conductors is easy to apply and results in inversion solutions requiring (typically) less than one minute of CPU time using current CPUs. This is expected to be an orders of magnitude improvement to any inversion scheme using for example smooth model voxel (cells) inversion schemes.

By using approximate solutions to show that at appropriate times, the EM response of a multiply folded sheet conductor in a layered medium can be largely controlled by the changes of the primary magnetic field at the conductor. Similar quick forward model and inversion schemes can be applied using folded conductors in layered earth models.

THE INFLUENCE OF DISCRETISING CONDUCTIVITY GRADIENTS IN THE 3D FINITE DIFFERENCE EM FORWARD MODELLING ALGORITHMS

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The objective of this paper is to seek a generalised understanding for the influence of incorporating the gradient of the model's physical properties (e.g. conductivity, velocity) in the forward modelling numerical algorithm. In order to take a step towards that, we examine an example from Geophysics for solving 3D Maxwell's equations using finite difference (FD) methods. The 3D FD methods to obtain discrete solutions of Maxwell's equations include the staggered-grid and balance methods. The balance method 3D algorithm exploits the

conductivity gradient in order to make the FD formulation a seven-point scheme and the resulting matrix a banded septa block diagonal but not symmetric. The staggered grid algorithm is free of conductivity gradient and results in a symmetric 13-diagonal banded matrix. The objective now is to examine and understand better the influence of the conductivity gradient incorporated in the FD equations on the accuracy of the electromagnetic (EM) modelling for two 3D benchmark models. We use three various discretisations (fine, mildly coarse, and coarse) for each model. The modelling results of each discretisation have been computed separately by the balance method and staggered grid method. We have found that the staggered grid method produces accurate results for all the three discretisations investigated. However, the balance method encountered some inaccuracies for the mildly coarse and coarse discretisations. This appears to be due to the presence of the conductivity gradient in the 3D modelling algorithm. The model studies also suggest that the thicknesses of the horizontal and vertical discretisations at the conductivity boundaries should be about 1/25 and 1/100 skin depth to maintain accurate modelling results when the conductivity derivatives exist in the 3D modelling algorithm.

THE BENEFIT OF COMBINING DOWNHOLE WITH SURFACE IP

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Resistivity and induced polarisation data are very useful for defining lithological boundaries, shear zones (often with conductive and chargeable graphite), and sulfide alteration zones. The useful depth for interpretation depends upon the effective current penetration and the magnitude of the measured voltages, which in turn are determined most often by surface conditions at the electrode locations. Downhole resistivity and IP measurements are relatively quick to acquire, and can add significantly to the depth of investigation of the surrounding surface survey. Examples over shear zones in southern Mali demonstrate the added depth information from inverting surface data with (1) downhole logging data and (2) data from bottom-of-hole current injection with surface receiver electrodes. The bottom-of-hole to surface surveying can be performed without any specialised downhole IP equipment, and, except in instances of specific interest around the borehole, is more valuable for complementing the surface data.

PETROLEUM 1.5

Reservoir Characterisation

RESERVOIR COMPARTMENT PREDICTION OF THE SIMPSON FIELD FROM THE GEOSTATISTICAL INVERSION OF AVO SEISMIC DATA

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The Simpson Field in the Barrow Sub-basin (Carnarvon Basin) is nearing depletion. Most of the producing wells are showing relatively high water cuts. Based on volumetric mapping and the drilling results from nearby analogous fields, some unproduced reserves are potentially remaining in the field within compartments separated by low permeability shale barriers. The challenge is to establish a methodology for identifying these compartments and to quantify unproduced oil.

The reservoir of the Simpson field is the Early Cretaceous Flag Sandstone. The reservoir zone has three distinct lithotypes: oil-saturated sandstone, water-saturated sandstone and shale. The shales encountered in the wells have a typical thickness of less than 3 m, significantly below standard seismic resolution. However, these lithotypes show good statistical separation of elastic properties (i.e. P-Velocity, S-Velocity and Density), so a properly-constrained geostatisitcal inversion can be used to predict the relatively thin shale barriers.

The geostatisitcal inversion is based on a Bayesian algorithm that relies on a set of input 'beliefs'. These beliefs take the form of variograms, multivariate probability density functions of elastic properties, stratigraphic relationships and the angle stack seismic and associated wavelets. A Markov Chain Monte Carlo method is used to randomly sample from the intersection of the uncertainty envelopes arising from all input beliefs, resulting in multiple elastic property and lithotype realisations. The analysis of the realisations output from the geostatistical inversion led to the identification of highly probable shale barriers and the quantification of unproduced oil.

UTILISING TUNING/AVO PHENOMENA IN PREDICTING OIL COLUMN HEIGHT – DEVELOPMENT DRILLING IN TUI/AMOKURA FIELDS, NZ

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A combined AVO/Tuning model has been used in predicting oil column height, and hence structure, in the drilling phase of the Tui area field development. In this development, horizontal production wells were designed to drain oil from three relatively small single well field discoveries in the Tui, Amokura and Pateke structures with total estimated gross 2P reserves of 28 MMBO. To date three horizontal development wells have been successfully drilled, two in Tui and one in Amokura.

The Paleocene aged Kapuni F10 sands occur at a depth of approximately 3700 mSS. The closure height and areal extents of these fields were initially mapped by converting time structure maps to depth using average velocities derived from stacking velocities.

Investigation of the AVO and tuning modelling using Vp, Vs and density logs from the Tui-1 and Amokura-1 exploration wells suggested that it was possible to map column heights using amplitudes extracted from the F10 sand seismic horizon. This modelling predicted an oil column height of 20 m at the crest of the Tui structure prior to the drilling of development well Tui-2H. In the same area column height of about 10 m was predicted using the average velocity based depth maps. Periscope results showed a maximum column height of 22 m, confirming the validity of the modelling.

The predicted increase of column height with amplitude has been further proven with the drilling of the Tui-3H and Amokura-2H

wells. Acquisition footprints that reduce the fidelity of the seismic amplitudes are the subject of planned reprocessing.

FESAUS 2

Advanced Formation Evaluation

THE BUILDING BLOCKS TO ENABLE THE BRIDGE TO BE CROSSED BETWEEN ROCK PROPERTIES AND SEISMIC

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Petrophysical reservoir results when applied to elastic moduli, help bridge the gap between the micro log- scale and the macro-seismic scale. Borehole *in situ* estimates of compression, shear and density produce mechanical properties of elastic moduli including Poisson's Ratio, acoustic-shear impedance, bulk and shear moduli; which when tied back to seismic, help derive estimates of lithology and fluid to reduce exploration and appraisal uncertainty and rock and borehole strength for drilling and production for fracture and sand control.

Rock property and fluid analyses can thus modelled by block averaging via lithology, fluid type and other upscaling techniques. Mechanical properties can then be calibrated to seismic at the wellbore for input into AVO package for modelling away from the wellbore. Thus seismic modelling and rock physics cross-plot techniques can be used to minimise exploration risk by help predicting lithology and fluid typing.

In an attempt to learn what impact changing fluids has on density and velocities, fluid substitutions are made using local estimates of oil API, gas gravity and brine salinity from nearby wells. A synthetic waveform can then be constructed from the density and fluid substitution cases, noting any phase shifts between substituting fluid from brine to hydrocarbons. Fluid substitution is determined using elastic moduli from measured P and S wave velocities with one pore fluid (brine); and transforming the rock elastic moduli to a new fluid ex light oil, and reconstructing the velocities corresponding to that change.

In conclusion, borehole acoustic and density measurements when integrated with rock physics and seismic have a wide range of applications in exploration, appraisal, development and formation evaluation.

DETERMINATION OF NMR T_2 CUTOFF FOR DUCTILE, LOW PERMEABILITY SHALY SANDSTONE

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For the past decades nuclear magnetic resonance (NMR) technology has gained acceptance as a petrophysical tool for evaluating reservoir quality. Comprehensive formation evaluation requires the determination of irreducible fluids, movable fluids, and permeability. The presence of clays, their occurrences and distributions however, in some reservoir rocks tends to introduce complexity in any formation evaluation activities. This can also cause problems for NMR log interpretation. In the presence of clays the most commonly used T_2 cutoff values, a constant value throughout a formation, seem to eventually yield inaccurate permeability estimates. Therefore, NMR measurements should be integrated with other measurements from conventional cores for a comprehensive formation evaluation, in which T_2 cutoff may vary for reservoir with different reservoir qualities. This paper presents results of a study that focuses on NMR measurements on Tirrawarra shaly sands taken from 3 wells situated in Cooper Basin, South Australia. The study suggests that the T_2 cutoff values for the samples vary significantly in order for NMR-derived irreducible water to match core-derived irreducible water. This is also true for NMR-derived permeability estimates when compared to measured permeability values. Comparisons between estimates produced using the normally used 'constant T_2 cutoff' and the suggested 'varied T_2 cutoff', as well as their effect on formation evaluation, are also discussed. In general, the results highlight the need to study T_2 cutoff values more directly for specific reservoir rocks before their practical uses in the field.

IN-HOUSE ANALYSIS OF NMR DATA FACILITATES CORE INTEGRATION FOR PERMEABILITY INTERPRETATION USING A MULTI-RESOLUTIONAL-CLUSTERING TECHNIQUE

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Nuclear Magnetic Resonance (NMR) log data has been acquired in exploration and appraisal wells to evaluate various reservoir properties such as irreducible water volumes, lithology independent porosity and to establish a permeability estimate. Historically NMR logs have been under utilised and often misunderstood resulting in a reliance on a 'black box' product direct from the Wireline contractor.

In order to maximise the value of the NMR data set a workflow of processing and interpretation from raw echo trains to final core integration was established in-house, utilising Geolog software. Taking ownership of the data in this way promoted NMR understanding within Woodside's Petrophysical community. This led to improved log quality control routines and an improved understanding of acquisition issues which help establish environments where NMR acquisition may not be favourable.

Working the data in-house allows for maximum integration of other well data and has resulted in some novel interpretation methodologies, principally to address permeability evaluation. One such approach is to apply a Mulit-Resolutional-Clustering (MRGC) solution engine to solve permeability from the NMR T_2 distribution and products from a core permeability training data set. This model can then be forward populated to un-cored wells with similar electro facies and NMR logs.

Areas of ongoing development include researching NMR gas response phenomena and attempting fluid substitution on the T_2 distribution to allow fluid independent cluster modelling.

NEAR SURFACE 5

Regolith

WHAT'S REGOLITH GOT TO DO WITH A LOAF OF BREAD, EUCALYPTUS OIL AND A GLASS OF CHARDONNAY?

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A glass of Chardonnay, eucalyptus oil and a loaf of bread all begin life with the plant interacting with its environment. For example, sensory characteristics of a glass of Chardonnay may be unique to the region from which the grape vine was grown in. A certain combination of climate, landscape, geology and regolith factors make up this 'terroir' characteristic in wines. This may also be the case for wine produced from different vineyards in a specific region and within a vineyard, as such combinations of factors change. Specific regolith features, such as soil texture and rooting depth can change in short distances, so that the yield or vigour of grape vines, wheat crops and eucalyptus species can subsequently be affected. This paper reports on the efficiency of geophysical methods, specifically radiometrics and ground penetrating radar, in identifying regolith characteristic which effect plant growth and their production endpoints.

MAPPING POROSITY AND DENSITY CHANGES IN SOIL AND REGOLITH FROM 256-CHANNEL RADIOMETRIC DATA

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Gamma ray emissions at 1120 keV and 1764 keV produced from ^{214}Bi (uranium-238 decay series daughter product) are emitted during the same decay reaction with the same probability of emission during decay. Thus, as uranium concentration varies, the ratio of 1120 keV to 1764 keV should remain stable. However, the lower 1120 keV energy is more susceptible to backscattering and normal Compton scatter than the stronger 1764 keV energy, where the probability for scatter to occur is correlated to the density and thickness of the absorber. In natural settings, soil and/or bedrock acts as an absorber. Consequently, as density or thickness of the soil and/or bedrock increases, the probability of scatter increases. Thus changes in the 1120 : 1764 ratio may indicate changes in soil thickness and/or density. By processing standard 256-channel radiometric data with multispectral processing techniques, ^{214}Bi 1120 keV gamma rays can be isolated in addition to standard ^{214}Bi 1764 keV. This case study illustrates how the spatial variability of 1120 : 1764 ratios highlight changes in soil thickness and/or density.

BIOENGINEERING OF SOIL PROFILES: INFLUENCE ON SOIL PATTERNING AND RADIOMETRIC SIGNALING

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New insights into biological functions of plant roots casts doubt on many entrenched abiotic theories on soil formation, to the extent that understanding processes in the Rhizosphere is now increasingly cited as the new frontier of regolith science. Critical field observations and information drawn from a number of disciplines suggests that many of these processes are linked to niche-building activities of higher plants. This paper examines some edaphic features and associated formative effects of competing plant communities in semiarid settings and presents evidence that bioengineering by higher plants and their associates is responsible for much of the chemical variation visible in radiometric imagery of the south-western Australian regolith.

13:00–14:30

MINERALS 1.6

Downhole/Gradiometry

AUTOMATED MULTI-SENSOR PETROPHYSICAL CORE LOGGING

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A GeoTek multi-sensor core logger (MSCL), which was originally developed to log soft-sediment cores, has been adapted to allow simultaneous measurement of a range of petrophysical parameters on diamond drill core. The system can measure density, P-wave velocity, electrical conductivity and magnetic susceptibility of either whole or split core. It also acquires high resolution colour imagery of the core. Modifications to the standard logging system and logging protocols were required to adapt the existing technology to work with diamond drill core from metalliferous mines. System operation, sensor development, sensor calibration, data accuracy, precision and repeatability are described in this paper. The GeoTek system is currently being used to acquire detailed petrophysical data on archival drill core for correlation with metallurgical parameters (AMIRA Project P843) but it has significant potential for use in many other applications.

GRAVITY GRADIOMETER SYSTEMS – ADVANCES AND CHALLENGES

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This paper will summarise advances in gradient sensor development, and will also look at deployment scenarios and gradiometer systems that have been successfully fielded. Finally, we will briefly address the most significant challenges associated with improved gravity gradiometer operational capability including instrument and system intrinsic noise, vehicle dynamic noise, terrain noise, geological noise and other noise sources.

DESCRIPTION OF AND RESULTS FROM A NOVEL DIRECT MAGNETIC GRADIOMETER

Howard Golden[1], Wayne McRae[1], Andrew Sunderland[2] and Alexey Veryaskin[1]*
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Project AMATI, so named in honour of the famous violin maker Nicolo Amati, is developing a direct string magnetic gradiometer capable of measuring cross-diagonal components of the magnetic gradient tensor. The device, being developed by Gravitec Instruments in conjunction with The University of Western Australia, employs a single vibrating string as the sensing element. The system operates at the string's 2nd violin mode at ~750 Hz. This 2nd violin mode is only sensitive to gradients, whilst the 1st fundamental mode (or quadrature of the 2nd mode) couples with

the magnetic field. This results in an instrument that has intrinsically infinite common mode rejection if its mechanical Q factor is infinite.

The instrument now operates with a common mode rejection ratio of about 107. It operates in a 10 mbar vacuum at room temperature, and is isolated from vibration by a three stage passive isolator. An alternating current of 0.3 A pumped along the string creates a force distribution along the string length in proportion to an external magnetic gradient. Inductive pick-up coils at the $^1/_4$ and $^3/_4$ points of the string detect gradient-driven displacements of the string of as small as 10^{-13} m/√Hz. The measured noise floor is less than 0.2 nT√Hz in an unshielded environment and is flat within the 0–1 Hz band. The ultimate sensitivity of the magnetic gradiometer will be limited by thermal noise in the string.

The system will be described in detail, field and laboratory data shown, and various challenges of this unique instrument discussed.

MINERALS 2.3

Modelling/Inversion

THE MAGNETOTELLURIC IMPEDANCE TENSOR AND ITS PROPERTIES

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A consistent definition of the linear relationship between the electric field true vector **E** and magnetic field pseudovector **H** yields a true magnetotelluric impedance tensor **T**. The true tensor nature of **T** allows diagonalisation in terms of classical eigenstate decomposition. Eigenstate analysis of **T** is in agreement with biorthogonal methods. Physical properties of the electromagnetic energy at the surface of the Earth define Hermitian forms that can be viewed as surface functions of the field polarisation parameters. Geometrical and physical properties of these surfaces establish the result that the eigenvectors of all the Hermitian forms have the same principal directions. This property links the vertical magnetic field with **T**, reduces the degrees of freedom of **T** from eight to six, provides a single principal direction that facilitates the interpretation of magnetotelluric data and shows that when **T** is defined, defining the tipper is unnecessarily restrictive. Synthetic data from 3D models is used to illustrate the main result.

ENHANCING THE EXPLORATION PROCESS

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Gaining information about subsurface geology, and potential ore deposits, with inexpensive techniques is the future of mineral exploration. The proper use of one of the most efficient techniques, geophysics, can only come when put in the appropriate context of geology and physical properties. Furthermore, when three-dimensional geological model building, detailed physical property analysis, and advanced geophysical inversions are combined, methods can be applied to answer specific exploration questions for targeting or delineation purposes.

Understanding how geology relates to geophysics is important both for supporting constrained geophysical modelling, and for extracting meaningful information from geophysics. To this end, physical properties, and how geology controls physical properties, play a key role and are a major focus of the integration process. In addition, methods of describing geology in a manner that can be incorporated into geophysical inversions provide another important link between geology and geophysics to aid in the integration process. Advanced inversion techniques are employed that capture all available information and associated uncertainties to ensure robust results are produced with an understanding of model reliability. With a sound prior knowledge of the geology and physical properties, resulting geophysical inversion models can finally be quantitatively interpreted in terms of geologic rock-type, structure, alteration, and mineralogy in order to provide the information needed by the exploration geoscientist now, and in the future.

A FAST APPROACH TO MAGNETIC EQUIVALENT SOURCE PROCESSING USING AN ADAPTIVE QUADTREE MESH DISCRETISATION

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The use of equivalent source processing is an important component of magnetic data interpretation in mineral and petroleum exploration. For example, such an approach has proven valuable for the regular gridding and denoising of magnetic data prior to later quantitative interpretations, such as full 3D inversion. The current practice for generating these equivalent source layers is to formulate the problem as an inverse problem, and seek to construct a 2D distribution (equivalent source distribution) of susceptibilities such that the observed data are reproduced. The drawback to this approach is in the computational costs and overall speed for large-scale problems. Since aeromagnetic method has become common in exploration, it is rare that the datasets acquired are small in spatial extent or in data volume. As a result, they can rarely be handled rapidly on a single workstation. One way to minimise the computational cost is to reduce the number of model parameters. We present an equivalent source processing technique that minimises the number of cells in the model domain via an adaptive quadtree mesh discretisation. The transition from the fine to coarse mesh grid is based on the total-gradient of the dataset, placing smaller cells on the edges of the anomaly where the susceptibilities have the greatest variation spatially. We show that the algorithm will perform over four times as fast as traditional equivalent source processing with a regular cell mesh yet preserves the same accuracy. We present a synthetic example for proof of concept as well as a field example.

PETROLEUM 1.6

Imaging

RESERVOIR IMAGING USING INDUCED MICROSEISMICITY

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Activities within a hydrocarbon reservoir, such as producing oil or injecting fluid, change *in-situ* stresses which consequently cause micro-earthquakes. The induced microseismic events are small earthquakes producing high frequency waves which can be used to give a better understanding of the hydrocarbon reservoir. However, induced microseismic events are too small in magnitude to be detected on the surface due to seismic wave attenuation through the overburden. Therefore, in order to make use of such induced microseismic waves for monitoring, characterising and/or imaging of the hydrocarbon reservoir, one should use buried sensors within monitoring wells. The microseismic events generated within a hydrocarbon reservoir as a result of the production activities are recorded. Then, the recorded first arrival times are used in inversion process to arrive at a detailed velocity model in the vicinity of the reservoir. The inversion process is based on a fast 3D finite-difference code using the eikonal equation to model the travel times of first arriving seismic events and; therefore, making the inversion of large 3D model practical. The methodology could lead to enhanced understanding and hence efficient management of the hydrocarbon reservoir. This in turn would enhance the understanding of fluid movements resulting in improved petroleum recovery from the reservoir.

THE LOCATION OF MICROSEISMIC EVENTS AND THE PROPAGATION OF RAY PATH AND GRIDDED TRAVELTIMES FOR DEPTH MIGRATION USING LOCALLY SPHERICAL WAVEFRONTS

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An efficient algorithm is presented that estimates the apparent source of a microseismic event from the first arrival clock-times at four receiver locations in a 3D volume. Wavefronts are assumed to be locally spherical in a constant velocity medium. Applications for identifying the apparent source range from monitoring hazardous geological sites, estimating the distribution of well fraccing material, the monitoring of sequestered CO_2, or global positioning from satellite data.

The clock-time of the source may also be estimated, extending applications to Kirchhoff depth migrations in which traveltimes on a grid may be computed directly, or may be estimated from traveltimes computed along raypaths. The traveltimes at additional grid points can be computed from the apparent source. In heterogeneous media, wavefronts may have an arbitrary shape, but can be considered to be circular over a small region in the neighbourhood of the known points. The velocity in this region is assumed to be constant and may be extended, without error, to enclose the apparent source point.

The method is illustrated with a 2D application in which circles are drawn with centres at three receiver locations with radii proportional to the corresponding clock-times. An additional circle that is tangent to the three original circles has its centre at the apparent source location and a radius proportional to the clock-time of the source. This source circle is found using the method of Apollonius. This method is then extended to 3D applications that require the clock-times at four receiver locations.

RESOLVING FAULT SHADOW PROBLEMS BY FAULT CONSTRAINED TOMOGRAPHY

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In many areas, so-called Fault Shadows are a serious hindrance to successful seismic imaging. The major part of this problem is caused by large velocity variations in fault zones. In this paper we examine different types of geological and imaging velocity anomalies in fault zones with all of them exhibiting large lateral velocity changes (short wave-length velocity variations) that cause seismic image distortions and non-hyperbolic moveout. Pre-stack depth migration with the proper velocity model is the only method that can solve this problem and improve the seismic image below fault zones.

We have developed a special and novel technique, Fault Constrained Tomography, to build the required high-resolution interval velocity models for fault zones. Distinctive features of this technique are:

- Fault planes are included into depth-velocity model;
- Non-hyperbolic Residual Curvature Analysis (RCA) on a dense grid of PSDM gathers;
- High-resolution 3D seismic tomography.

We have successfully employed the Fault Constrained Tomography technique on several 3D seismic datasets, and will discuss the methodology and results in this paper.

PETROLEUM 2.3

Rock Properties

ELASTIC AND PETROPHYSICAL PROPERTIES OF SHALES

Dave Dewhurst[1], Tony Siggins[2], Utpalendu Kuila[1], Ben Clennell[1], Mark Raven[3] and Hege Nordgård-Bolås[4]*
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Although shales comprise a large proportion of the sedimentary pile in many hydrocarbon-rich regions, their behaviour is not well understood from basin scales right down to the microscopic physics of particle interactions. Shale properties impact significantly on exploration, development and production costs through the effect of seismic anisotropy on imaging and depth conversion, the role of shales in 4D seismic response, in addition to associated issues such as pore pressure prediction and prediction of dynamic Poisson's ratio.

Tests were performed on shales from the North Sea, Carnarvon and Officer Basins with a view to measuring their petrophysical and ultrasonic properties. Ultrasonic tests were carried out to evaluate the full elastic tensor and its variation with stress. Tests on four North Sea shale core plugs with homogenous properties and composition showed significant and unexpected variations in both petrophysical properties and ultrasonic response with respect to stress. Variability in dielectric properties could be explained from fabric studies using both SEM and CT scanning. The anomalous ultrasonic response is more difficult to visualise and may be due to different microfracture distributions within core plugs. Ultrasonic tests evaluating the full elastic tensor on single shale core plugs show smoother responses in terms of velocity, elastic coefficients and anisotropy over a larger stress range and are more readily interpretable in terms of fabric and composition. The use of petrophysical evaluation has proved invaluable in these tests, helping us to identify anomalous responses in otherwise seemingly homogenous bulk rock.

ROCK PHYSICS, TREND CURVES AND FLATSPOTS

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Seismic amplitudes and AVO have been used successfully in exploration worldwide. We present a general geologically-based methodology to characterise the expected amplitude and AVO behaviours of reservoirs and seal facies in a basin. Fundamentally, we employ a postulated geological depositional mechanism for a basin and produce a consistent rock physics model based on well data and the geological model. The result is summarised in a series of depth trend curves for rock properties and anticipated seismic responses. We illustrate the use of these trends to predict amplitude and AVO responses throughout the basin. We then show several examples of the application of this methodology in various basins across the world, and also apply this technique in a predictive mode for the North Carnarvon Basin in the North West Shelf of Australia. A by-product of the technique is the verification of the validity of the amplitude changes and flat-spots often seen in seismic data, which can result from physical property changes across fluid interfaces. For example, seismic flat-spots cross-cutting dipping stratigraphy are commonly observed within the Mungaroo Formation of the Exmouth Plateau area of the North Carnarvon Basin. We show techniques for quantifying the consistency of flat-spots in 3D, assessing amplitude conformance with structure in map view and automatically determining fluid contact levels with examples from several basins.

INVESTIGATION OF SHEAR WAVE ANISOTROPY IN DEVIATED WELLS NEAR A SALT STRUCTURE IN THE GULF OF MEXICO

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In this study, we investigate a technique to separate structure-induced and stress-induced shear wave velocity anisotropy from cross-dipole sonic imager (DSI) shear wave velocity data. The investigation focuses on anisotropy data from deep water, sub-salt wells in the Gulf of Mexico. The cross-dipole tools measure an apparent fast direction in plane that is perpendicular to the wellbore. We show how it is possible to differentiate between structure-induced apparent fast directions due to bedding (confirmed independently from dipmeter logs) and stress-induced shear wave anisotropy and can be used to infer principal stress directions. The number of wells drilled in complex environments (such as near salt structures) continues to increase. These wells are some of the most expensive wells to drill and are prone to numerous drilling problems that drastically increase their associated costs. Better understanding of the structural influences on velocity anisotropy near salt leads to better sub-salt imaging and targeting of reservoirs. While better understanding of the geomechanical setting results in more successful drilling and completion of these wells. The stress-induced fast directions rotate along the length of the wells. Some of these rotations may indicate the presence of active faults, while others may result from the salt-induced stress perturbations expected in the region. We also examine approaches for determining the effects of structure-induced velocity anisotropy on the seismic signal and approaches for converting apparent stress-induced fast directions observed in the dipole sonic shear data to true principal stress directions.

FESAUS 3

Sonic Applications

A REVIEW OF LWD SONIC LOGGING TECHNOLOGIES AND APPLICATIONS IN AUSTRALIA

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LWD Sonic logs are used extensively in Australia, where development of many key technologies have been tested and proved. In recent years, there have many significant advances in LWD sonic tools and analysis techniques, including shear in slow formations, multipole tools, radial profiling, large diameter tools, cased hole logging and CBL analysis. This presentation will review the existing technologies and applications in generic terms (without branding), comparing the available services with wireline technologies and presenting examples from Australian fields.

PETROLEUM BOREHOLE SONIC ACQUISTION AND INTERPRETATION – RECENT ADVANCES

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Petroleum related borehole acoustic measurements have applications in the domains of geophysics, petrophysics, well-completion and geomechanics. In recent years, borehole sonic technology has experienced rapid development. Innovations in the acquisition of high fidelity, broad band waveform sonic data, advanced waveform dispersion analysis, and approaches to more accurately quantify acoustic anisotropy are changing industry perspectives and has encouraged interpreters to reassess the full benefit of borehole sonic log data.

Advanced slowness frequency dispersion analysis yields new information about the type of acoustic anisotropy present in the reservoir and the near wellbore environment, whether the rock has been altered by the drilling process and to what extent. In extremely slow formations and other difficult acquisition environments dispersion analysis is used as an excellent quality control indicator to guarantee that the computed slowness accurately represents formation properties.

Newly developed borehole sonic radial slowness measurements enable an increased understanding of the near wellbore environment and has applications to wellbore completion and geomechanics. Improvements in Stoneley wave acquisition and logging tools that are fully characterised for their acoustic response have a higher sensitivity to fluid mobility. As such, the estimation of reservoir formation permeability from Stoneley waves is greatly enhanced.

With reference to data predominantly acquired in China this paper focuses on the new developments in data acquisition, Slowness frequency dispersion analysis, Stoneley permeability, azimuthal and horizontal anisotropy and slowness radial profiling.

ESTIMATION OF SHEAR WAVE TRANSVERSE ISOTROPY FROM BOREHOLE ACOUSTIC DATA WITH THE HELP OF RESISTIVITY ANISOTROPY MEASUREMENTS

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Seismic anisotropy is very important for exploration and exploitation of reservoirs. The acquisition of borehole acoustic data helps to quantify seismic anisotropy. The main borehole acoustic acquisition modes are **monopole**, **dipole** and **cross dipole**. **Dipole** acquisition measures shear wave slowness along the borehole axial direction. **Cross dipole** acquisition measures azimuthal (axial) shear wave anisotropy around the borehole. **Monopole** acquisition measures P, refracted S and Stoneley wave, the Stoneley being sensitive to horizontal (radial) shear slowness.

In the basic scenario of borehole being normal to horizontal formations, combining Stoneley and dipole or refracted S measurements makes it possible to determine vertical-versus-horizontal transverse anisotropy (VTI).

In the more common scenario of the borehole intersecting formations at a relative dipping angle, additional information is required. In such deviated well cases, VTI anisotropy is quantified by combining Stoneley measurement with the cross dipole azimuthal anisotropy measurement. Results are best interpreted with the integration of the continuous formation dip and azimuth information provided by the resistivity anisotropy measurement.

Resistivity anisotropy is measured with the help of a multi-component induction tool. This tool is made out of three mutually orthogonal transmitter-receiver pairs that measure the full magnetic tensor at multiple frequencies. Full magnetic tensor can be inverted to determine formation horizontal and vertical resistivity and also structural formation dip and azimuth.

This presentation integrates borehole acoustic data with the formation dip and azimuth from resistivity anisotropy measurement for shear anisotropy estimation (Thomsen parameter γ). By correlating between P and S wave anisotropy, results could be used for seismic migration.

NEAR SURFACE 6

Regolith

ELECTROMAGNETIC SOUNDINGS OF THE REGOLITH AT KALKAROO MINERAL PROSPECT, CURNAMONA PROVINCE, SOUTH AUSTRALIA

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Large parts of Australia are blanketed with a thick regolith that masks mineral deposits. Time Domain Electromagnetic (TEM) technique is a proven method for imaging structures below or within the weathered overburden. Four NW-SE SIROTEM transect lines (three 1.5 km long and one 2.5 km long) were conducted over a magnetic anomaly in the Cu–Au Kalkaroo prospect in the Curnamona Province (S.A.). The TEM survey geometry used 100 m square transmitting loops with an in-loop central receiver coil and 100 m station spacing to maximise penetration into the electrically conductive overburden. Initial results of the survey, following a 'STEMINV' smooth model inversion process, suggest the TEM soundings penetrate to a depth of 100–150 m and reveal the presence of conductive regolith overlying a resistive zone. Furthermore, the 2D depth-resistivity image obtained for all the TEM transects clearly indicates the presence of a highly conductive layer within the regolith at a depth of about 20–50 m. Through correlation with nearby drillhole data and potential field data, this conductive zone is interpreted to be the Namba Formation. The TEM results also indicate some of the structural features of the basement.

A SEMI AUTOMATED TECHNIQUE TO REGOLITH-LANDFORM MAPPING IN CENTRAL WEST AFRICA

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Extensive airborne surveys including Radiometric, Magnetic and Electromagnetic datasets were flown over large parts of Niger and Nigeria for the respective government geological surveys. The new data were used to generate a geomorphological map product. It was decided that Regolith-Landform mapping would present the best product and the RT-map system developed at Geoscience Australia for Australian regolith was adapted to African regolith.

Datasets included Radiometrics (250 to 400 m line spacing), Shuttle Radar Topography Mission (SRTM) Digital Terrain Models (DEM) with a 90 m cell size, Landsat ETM7+ with a 30 m cell and 15 m panchromatic band and where available or appropriate Magnetic and Electromagnetic data was used.

Mapping was completed at various scales according to clients' requests ranging from 1 : 50 000 to 1 : 250 000. Due to the large scale of the surveys a method was required that was as fast and as automated as possible. Various GIS based techniques were adopted to achieve this including:

- Modelling of SRTM to generate drainage lines;
- Spatial statistics and residuals analysis on radiometric grids;
- Contouring of landsat to delineate areas of *insitu* and transported regolith.

With high resolution datasets becoming more available automated mapping techniques will become increasingly viable. With DEMs from LIDAR (Light Detection and Ranging), landform delineation could be automated using feature extraction and with the high resolution datasets much more accurate drainage line delineation would be possible. Further sub-metre resolution satellite imagery (QuickBird and Ikonos) will make finer mapping scales possible and mapping at regional scales more accurate.

POROSITY AND SALT LOAD PREDICTION FROM AIRBORNE EM AND BOREHOLE EC

Yusen Ley-Cooper[1,2] and James Macnae[2]*
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Dissolved salt in aquifers is a potential threat to fresh water resources and the environment. Interpolated grid maps at aquifer depths, derived from borehole EC measurements on water samples, are combined with more detailed bulk electrical conductivities from airborne electromagnetics to provide detailed estimates of total dissolved salt load and subsurface porosity values. A resistive matrix host assumption implies that our calculated porosity and salt load values are maximum values. This mapping technique is a large area coverage remote senor method which has been tested in different areas of the salt-threatened Murray-Darling Basin. The predicted porosity values derived from airborne have been verified with measured porosities for borehole core samples. This technique provides extensive information on the hydraulic properties of aquifers, important for quantitative hydrology.

15:00–17:30

MINERALS 1.7

Instrument Forum

DESCRIPTION OF AND RESULTS FROM A NOVEL BOREHOLE GRAVITY GRADIOMETER

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Gravitec Downhole Instruments Ltd (GDI), a joint venture between Gravitec Instruments Ltd and Shell Technology Ventures (now Kanda Capital), in conjunction with QinetiQ Ltd, is developing the Scorpius borehole gravity gradiometer employing Gravitec's advanced string gravity gradiometer technology.

The sensor comprises a 38 cm long thin ribbon of material held between two fixed end points. Inductive readouts mounted at the ¼ and ¾ positions along the length of the ribbon detect ribbon perturbations of as low as 10–14 m caused by the local gradient. Any variations in the uniform field along the ribbon cause the ribbon to deflect in an S shaped mode with minima at the end points and in the centre. In a borehole the sensor is able to directly measure the off diagonal gravity gradient components (T_{xz} and T_{yz}).

Forward numerical modelling has confirmed that the proposed in-hole measurement components will be sufficient to define changes in reservoirs caused by depletion over time. Further, the modelling has shown that the target sensitivity of the sensor will be suitable for detecting the expected changes in reservoir density. The sensor has been demonstrated in laboratory tests, and is now undergoing further engineering prior to being deployed in a tool suitable for the petroleum borehole environment.

HELICOPTER TRIAL OF MAGNETIC TENSOR GRADIOMETER

Keith Leslie[1], Kyle Blay[1], David Clark[1], Phil Schmidt[2] David Tilbrook[1], Marcel Bick[1] and Cathy Foley[1]*
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A SQUID (Superconducting Quantum Intereference Device) based rotating tensor gradiometer has been test flown in a helicopter towed bird over a magnetic dipolar source. The bird was instrumented with fluxgates, tiltmeters, a gyroscope and GPS receivers to assist in levelling and positioning the bird. After correcting for pitch, roll and yaw of the bird, the gradient tensor measurements along flight lines compare well with those calculated for the flight lines relative to the magnetic source.

The uses and advantages in mineral exploration of magnetic tensor gradiometry have been discussed at previous ASEG meetings (2001 and 2004) and among other things include the benefits of vector surveys without the disadvantage of extreme sensitivity to orientation, desirable mathematical properties of true potential fields (important in areas with strong anomalies), allowing rigorous continuation, RTP, magnetisation mapping, etc. and redundancy of tensor components giving inherent error correction and noise estimates.

A novel inversion/deconvolution approach has been developed for locating and characterising dipole sources. Inversion using Euler deconvolution has also been developed for locating a wider set of geometries generally encountered in mineral exploration, such as spheres, sheets and pipes. A wide range of new types of processed data are possible, including invariants, directional filters and depth slicing.

MINERALS 2.4

Modelling/Inversion

MATCHING MAGNETIC SOURCE MODELS TO GEOLOGY – AN EXAMPLE FROM THE BENDIGO 1 : 250 000 MAP SHEET, VICTORIA

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Attributing geology in the generation and interpretation of subsurface models is crucial to any inversion. In some cases the geology is well known and linkage with a model can be made with confidence, in other cases linkage is necessarily speculative. This paper illustrates design and implementation of a database of geologically attributed magnetic models, using examples from the Bendigo map sheet in Victoria. The Microsoft Access database allows a user to assign stratigraphy, lithology and any magnetic property measurements to source bodies. Magnetic susceptibility values are critical in linking models with geology, and the database distinguishes between measured susceptibility values, proposed values and values derived from inversion. The database also incorporates special magnetisation considerations, such as demagnetisation and remanence. The database can be searched by region, characteristics of anomalies, magnetisation, lithology, stratigraphy or source body. To address non-uniqueness of magnetic models the database accommodates sensitivity studies. Because the database is spatial it can supply interpretation aids, such as hyperlinked images of anomalies or model sections, to geologists working in a GIS environment. The database can be used, just as are analogues in geological interpretation, to highlight similarities and differences with well studied areas. Once the database reaches a critical size and spans sufficient geological settings it will be developed into an expert system with the objective of proposing probable source lithologies for

magnetic anomalies in new areas. Early experience in using the database has emphasised the restrictions that are imposed on interpretations by limited availability of physical property measurements.

GEOLOGICAL INTERPRETATION OF POTENTIAL FIELD INVERSE MODELS USING AUTOMATED CLASSIFICATION

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Conventional interpretation of three dimensional potential field inverse models usually involves thresholding the model volume to create isosurfaces that hopefully outline the subsurface distribution of geological units. Unfortunately models are inherently smooth and the choice of the most appropriate value for isosurface generation is seldom clear-cut. However if both density and susceptibility models are available for an area then the combined dataset can be interpreted by classification using techniques developed for multi-band image data. Classification can be conducted using unsupervised or supervised techniques using either hard or soft classification algorithms. Supervised classification can be based on measured petrophysical data or on model values in areas where the surface or subsurface geology is well established. Soft classifiers are generally more appropriate than hard classifiers for this purpose since they better reflect the inherent geological ambiguity associated with often overlapping physical property distributions. Geological classification of potential field inverse models is illustrated with examples from Tennant Creek and western Tasmania.

A RAPID ALGORITHM FOR SELF-POTENTIAL DATA INVERSION WITH APPLICATION TO MINERAL EXPLORATION

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We have developed a new inversion algorithm to successively determine the depth (z), polarisation angle, and the electric dipole moment of a buried structure from the self-potential (SP) data measured along profile. By utilising the entire values of the SP profile, the problem of depth determination is formulated into the problem of solving a non-linear equation of the form f(z) = 0. Using the estimated depth and by applying the least-squares method, the polarisation angle is then determined. Finally, having known the depth and polarisation angle, the electric dipole moment is determined in a least-squares sense. The proposed SP inverse algorithm has been derived for semi-infinite vertical cylinder, infinitely long horizontal cylinder, and sphere anomalous bodies. The method is tested on synthetic examples with and without random errors, and applied to a field example from Germany for mineral exploration. The estimated depths and other SP model parameters are found in good agreement with the known actual values. The results obtained will be presented and discussed in the conference.

PETROLEUM 1.7

Imaging

IMAGING OF FRACTURES AND FAULTS INSIDE GRANITE BASEMENT USING CONTROLLED BEAM MIGRATION

Don Pham[1]*, Jason Sun*[1]**, James Sun*[1]*, Qingbing Tang*[1]*, Graeme Bone*[2] *and Nguyen Truong Giang*[2]
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In this paper, we present a reprocessing case study that applied the latest processing technologies to improve the seismic imaging inside the granite basement reservoir. The highlight of this effort is the application of the latest Controlled Beam Migration (CBM) technology, and a new method of scanning velocity below the basement.

In the study area offshore Vietnam, imaging inside granite basement for fractures and faults has been a challenge for both exploration and production. Two of the main challenges are the poor signal to noise ratio inside the basement and the imaging of the steeply dipping fractures. Objectives of previous processing efforts in 2002, also focused on improving the imaging but utilised Kirchhoff pre-stack depth migration, which included horizon-based model building up to the basement and constant velocity sweep below the basement. Even with this effort, the image was noisy inside the basement and hard to interpret. In particular, it was hard to tell the vaguely visible steeply dipping fractures from Kirchhoff migration artifacts.

With recent advances in imaging technology and velocity model building, the same data was reprocessed through pre-stack depth migration, and significant improvements in signal to noise ratio and steep dip imaging inside the basement was achieved.

UTILISING THE TWO-WAY WAVE EQUATION: REVERSE TIME PRE-STACK DEPTH MIGRATION

*Matthew H. Karazincir, Clive M. Gerrard, Andrew S. Long**
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Use of the two-way wave equation offers significant opportunities to utilise reflections from highly dipping events, turning waves, multiply reflected events and ghosts contained in the input seismic data to generate superior seismic images. Conventionally, the method has been very computationally intensive and, therefore, has been considered impractical for production 3D depth imaging projects. Here we describe an efficient algorithm that can be used on large scale 3D seismic data. To make it practical and efficient we employ explicit second-order in time and high-order in space domain finite differences, and use numerous domain decomposition and threading techniques to split the image cube amongst multiple CPU's, when necessary. High-order spatial finite differences handle numerical dispersion, and allow larger time steps than

those possible with the more conventional pseudo-spectral method.

Briefly, reverse time pre-stack depth migration is performed by solving the two-way acoustic wave equation. First, a forward extrapolation of the source wavefield in time is performed, and the wavefield is saved for use during application of the imaging condition. Second, the receiver wavefield is backward propagated in time; and, finally, the imaging condition is applied after each backward propagation time step. The results are summed to form a partial image volume. Reverse time pre-stack depth migration is applied to consecutive shot gathers, and their image volumes are spatially summed to produce the final pre-stack depth image. We will show an overview of the method along with 2D and 3D synthetic and real data examples.

A WAVE PROPAGATION BASED METHOD FOR IMPROVED SEISMIC FRACTURE PREDICTION

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We developed a wave propagation based method to improve the quality of seismic P-wave fracture prediction. The improvement is achieved through reducing the overburden influence superimposed on to a target layer. Rather than relying on evaluations of the layer's properties across an interface, our method predicts fractures using two 'fracture functions' estimated from the top and bottom reflections of a target layer. The two functions are firstly served as a measure of overburden influence, and then incorporated in the inversion to minimise the overburden effect. This results in improved fracture prediction for a target layer. Tests on the physical model data suggest the viability of the method in obtaining improved fracture information for an arbitrary layer. Operating the method requires only the picking of reflections from pre-stack data and is applicable to a wide range of seismic surveys including 2D, 3D and VSP.

NIP TOMOGRAPHY INVERSION: A NEW IMPROVED METHOD FOR VELOCITY MODEL ESTIMATION: A SYNTHETIC DATA EXAMPLE

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The NMO/DMO/stack method is a traditional and well-known method in the oil industry that needs an accurate macro velocity model to image the subsurface structures. Making such a macro velocity model is a time consuming process that is error prone. Newly introduced common-reflection-surface (CRS) stack is a data driven method which is independent of velocity information apart from the surface velocity. It comes from common reflection point (CRP) trajectory concept for finite offset. In NMO/DMO/stack the stacked data are obtained from a summation over a curve along the offset coordinate but the principal of CRS stack is to sum along a surface of specular contributions from a segment of a reflector instead of reflection point. The summation over a segment of a coherent reflector drastically improves the signal/noise (S/N) ratio as the stacked data will show. An important aspect of the method is that the estimated parameters provide us with significant information on the subsurface structure. These are three new parameters called kinematic wavefield attributes α, RN and RNIP. The parameter α is the emergence angle of normal-ray which will be later for a normal-ray map migration. RN is the curvature of the exploding reflector wavefield measured at the surface and RNIP is the curvature of normal-incidence-point wave which could be used later to yield information on the propagation velocity and inversion NIP tomography. Here we processed synthetic data to derive a zero offset or CRS stacked section with a high S/N ratio and better continuity of the reflection events.

INVESTIGATION OF OVERBURDEN HETEROGENEITY EFFECTS AND THEIR REMOVAL THROUGH HIGH RESOLUTION TOMOGRAPHY AND PRE-STACK DEPTH MIGRATION

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Severe seismic velocity undulation spread throughout the study area has hindered precise depth prediction using conventional methods. With forward modelling and detailed data review, the origin of the undulation was identified, necessitating precise depth/velocity prediction through appropriate velocity modelling and pre-stack depth migration.

Analysis of synthetic seismic pre-stack gathers, generated from 2D forward modelling, demonstrated that small shallow velocity anomalies such as channels could give rise to apparent seismic RMS velocity artefacts at deeper target levels. It was identified that the sense of the deep velocity anomalies are opposite to the corresponding shallow velocity anomalies, i.e. shallow high velocity anomalies produce low velocity artefacts in the deep and vice versa. By examining coincident patterns of time-thickness, amplitude and deep seismic RMS velocity, corresponding to the phenomenon predicted by forward modelling, shallow heterogeneous layers causing target velocity undulation were delineated.

Forward modelling suggested that pre-stack time migration is inadequate for modelling velocity anomalies when the width of shallow lateral velocity heterogeneity is less than the maximum the offset length. Alternatively, the solution requires the implementation of pre-stack depth migration using precise shallow velocity models.

Shallow heterogeneous velocity patterns were successfully identified by employing combined layered/blocky and global/smooth modelling derived from dense residual moveout picking and 3D finite-offset tomography. This approach helped to eliminate deep velocity artefacts and enabled correct representation of deep depth structure.

PETROLEUM 2.4

Rock Properties

ROCK PHYSICS MODELLING OF ELASTIC PROPERTIES OF ROCKS SATURATED WITH HEAVY OILS

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Success with heavy oil production depends as much on knowing the geology of reservoir as it does on understanding the fluid properties of the reservoir. Heavy oils are defined as having high densities and extremely high viscosities. Due to their viscoelastic behaviour the traditional rock physics based on Gassmann theory becomes inapplicable in principle. In this paper, we use equivalent-medium approach known as coherent potential approximation or CPA to estimate the properties of a mixture of an elastic solid and a viscoelastic fluid. Such mixtures are modelled as solids with elliptical fluid inclusions when fluid concentration is small, and as suspensions of solid particles in the fluid when the solid concentration is small. This approach is consistent with the concepts of percolation and critical porosity, and allows one to model both sandstones and unconsolidated sand. We also use Hashin–Shtrikman (H-S) bounds to calculate frequency-dependent moduli of rock-heavy oil mixtures. We substitute the fluid shear modulus by the complex one following a modified Maxwell model of a viscoelastic medium. As expected, the CPA estimates lie between lower and upper H-S bounds. We compare the obtained estimates with the properties predicted by the extended Gassmann's equation for the viscous pore fluid modelled as a specific generalised Maxwell body. We also apply the numerical rock physics approach to model the properties of rock-heavy oil mixtures for the range of heavy oil viscosities. Comparison of the obtained results shows that both the Gassmann and numerical predictions reasonably agree with the CPA estimates.

SUBCRITICAL CRACK GROWTH IN ROCKS UNDER AQUEOUS ENVIRONMENTS

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Study of time-dependent fracturing behaviour of rock is essential to ensure the long-term stability of structures in rock mass, such as underground power plants, caverns for storing liquefied petroleum or natural gas, or repository for radioactive wastes in underground. Subcritical crack growth is one of the main causes of time-dependent fracturing in rock. In this study, subcritical crack growth in rock was investigated in distilled water (pH = 6) and aqueous solution of sodium hydroxide ($NaOH_{aq}$, pH = 11). Especially, comparing the results in water to those in air, the effect of water was investigated. Additionally, the effect of pH in aqueous environment was also investigated. The rock samples were andesite and granite. The relation between the crack velocity and the stress intensity factor was investigated by the Double-Torsion method. In this study, all experiments were conducted at a constant temperature (285 K). It was shown that the crack velocities in water were higher than those in air. These results are in accordance with the facts that stress corrosion is the main mechanism of subcritical crack growth and water is the corrosive agent. Comparing the results in $NaOH_{aq}$ to those in water, it was shown that the crack velocity at the same stress intensity factor was independent of pH. This result is different from the conventional concept that the hydroxyl ion acts as the corrosive agent for stress corrosion. It is concluded that water accelerates the crack velocity and pH has little effect within the environmental conditions in this study.

ELASTIC PROPERTIES OF SHALES WITH RESPECT TO SILT FRACTION

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Elastic properties of shales are important for quantitative interpretation of seismic response, detecting high pore pressure before borehole drilling, and understanding overburden response during production. Modelling shale properties is difficult however as elastic properties of individual clay minerals are hard to measure directly. We use a transversely isotropic differential effective medium approach to calculate elastic constants of shales with different silt fractions. Increasing silt fraction from 0 to 25% results in increase of elastic constants C_{11}, C_{33}, C_{13}, C_{44} and C_{66} on 21%, 21%, 6%, 34% and 29%, respectively, whereas 75% of silt change the elastic constants on 53%, 60%, –1%, 77% and 66%, respectively, in comparison with the constants of pure clay. These non-uniform alterations of elastic constants might lead to changes in elastic anisotropy. Thus Thomsen's anisotropy parameters ε, γ, and δ which describe the variation of P- and SH-wave velocities as a function of polar angle with respect to symmetry axis are also calculated. ε decreases by 2% and 47% with increase of silt fraction from 0 to 25% and 75%, respectively. γ decreases by 15% and 65% by adding 25% and 75% of silt, respectively. δ increases by 35% with increase of silt fraction from 0 to 25% and changes sign when silt fraction reaches 72%. The results show that the presence of silt in shales cannot be neglected as it substantially increases compressional and shear velocities and reduces anisotropy. These theoretical results are compared with laboratory measurements of ultrasonic data on shales.

LABORATORY MEASUREMENTS OF STRESS-INDUCED VELOCITY ANISOTROPY IN UNCONSOLIDATED SANDS

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Seismic properties of granular sediments are sensitive to stress. When a stress is applied to the media non-hydrostatically, its elastic

properties and, therefore, the seismic velocities, can become anisotropic (stress-induced velocity anisotropy). We have developed an experimental device for measuring the transverse isotropic (TI) elastic properties of sediments under uniaxial strain conditions. The *phased array compaction cell* utilises matched sets of P- and S-wave ultrasonic transducers located along the sides of the sample and an ultrasonic P-wave phased array source with pinducer receiver on the ends of the sample. The phased array provides plane P-waves that are used to measure phase velocities over a range of angles. From these measurements, the five elastic constants for TI media can be recovered as the sediment is compacted, without the need for sample unloading or reorienting.

Our initial experiments have demonstrated significant stress-induced velocity anisotropy in unconsolidated dry sand. P-wave anisotropy of 20% has been observed under an axial stress of 5 MPa. The potential effects of stress-induced anisotropy in unconsolidated sand reservoirs may significantly impact seismic imaging and property estimation from seismic data. There are also implications for the analysis of time-lapse seismic data from unconsolidated reservoirs undergoing pressure depletion from production as the induced affect of anisotropy on the Vp/Vs ratio can be similar in magnitude to the difference between oil and gas.

FESAUS 4

Reservoir Solutions

TUI FIELD GEOSTEERING

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AWE's Tui Area Development is located on the offshore Taranaki Basin, New Zealand. It comprises three oil pools in low relief anticlinal closures, reservoired in upper shoreface sands with about 18% porosity and 1 Darcy permeability. As strong bottom water drive was expected, a key objective in design of the horizontal production wells was to place the wellbores as close to the roof as possible, which required that the wells be geosteered. Various methods were assessed but in the end Schlumberger's PeriScope 15 tool was selected. Modelling of tool response in the Tui environment, where reservoir resistivity is an order of magnitude greater than the overlying shale and underlying water sand, indicated that the boundaries above and below would be resolved at distances of 2.5 to 3.5 m from the wellbore. In practice, the tool performed better than expectation and four horizontal wells were drilled to a total distance of 5718 m almost entirely within the reservoir. The profiles from the PeriScope inversion results were used to remap the field postdrill and reduce structural uncertainty. Most importantly, the wellbores were placed an average of 1.5 m below the roof which will optimize oil recovery from the field.

4D PRESSURE PILOT TO STEER WELL SPACING IN TIGHT GAS PRODUCERS

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Obtaining reliable and accurate formation pressures in micro-Darcy rock has been a formidable challenge for tight gas producers. However, it is these pressures that give the most unambiguous data to identify unique reserves. They help to determine the drainage areas as well as appropriate well spacing for tight gas reservoirs.

Gauge configuration was designed to collect daily pressures in numerous sands without compromising future production. Combining existing systems offered by two contractors into an integrated package mounted external to the casing enabled us to acquire this data, while still allowing for hydraulic-fracture completion and normal production in the future.

Two wells were drilled with one in the maximum horizontal stress direction (aligned with the hydraulic fracture azimuth) and one perpendicular to this orientation. Each well was placed at ~660 ft from an existing producing well, corresponding to a conventional 10 acres pattern. Twenty pressure sensors were distributed over the 6000 ft productive interval. One well showed significant depletion in the majority of the sands whereas the other displayed very little depletion.

This pressure data was used to history match dynamic models, which were subsequently used to evaluate numerous well densities and patterns. This formed the basis for a downspacing application, which was later approved by the government.

Obtaining pressure data with dozens of permanent gauges is expensive, but we are convinced that given the significant impact on gas in place, recoverable gas, drainage area and ultimately well spacing, it is cost effective.

SHALE GAS ROCK PROPERTIES PREDICTION USING ARTIFICIAL NEURAL NETWORK TECHNIQUES AND MULTI-REGRESSION ANALYSIS: AN EXAMPLE FROM A NORTH AMERICAN SHALE GAS RESERVOIR

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Estimation of reservoir parameters has always been a challenge for shale gas reservoirs. This study has concentrated on neural network technique and multiple regression analysis to predict reservoir properties including porosity, permeability, fluid saturation and total organic carbon content from conventional wireline log data for a large North American shale gas reservoir. More than 262 core analysis data from three wells were used as 'target' and 'response' for neural network and multiple regression analysis. Common log data available in three wells including GR, SP, RHOB, NPHI, DT and deep resistivity were used as 'input' and 'predictor'.

This study shows that reservoir parameters could be better estimated using the neural network technique than through multiple regression. The neural network method had a correlation coefficient greater than 80% for most of the parameters. Although providing a set of algorithms, multiple regression analysis was less successful for predicting reservoir parameters.

OPERATIONAL CONSIDERATIONS FOR OPTIMISING PRESSURE TEST RESULTS USING LWD FORMATION TESTER

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Acquisition of formation pressure tests while drilling can reduce rig time and lead to potential cost savings in comparison to wireline pressure tests. Applying logging while drilling (LWD) pressure testing technology in highly deviated or horizontal wells in particular results in considerable rig time savings where pipe-conveyed wireline pressure tests would otherwise have been run.

An awareness of the differences between LWD and wireline formation pressure test borehole environments will allow for better pre-job planning and data acquisition techniques. In the LWD environment, due to the short time interval between drilling and pressure testing, a mudcake may not be fully formed at the time of the pressure test and continued mud filtrate invasion into the formation during the test may result in supercharging especially in low permeability formations. Operational procedures to minimise supercharging effects will be discussed. Other parameters to consider for improving pressure measurement quality include depth control and pressure repeatability during the test.

This presentation looks at the operational considerations required to enhance tool performance and measurement quality and attempts to compile the experiences and learnings in running the LWD Formation Tester.

PRODUCTION OPTIMISATION IN HORIZONTAL WELLS BY THREE-PHASE FLOW QUANTIFICATION: CASE STUDIES FROM MALAYSIA

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Accurate inflow determination of oil, gas and water is fundamental to understanding the behaviour and performance of a well, and critical for developing optimum production strategies and designing remedial workovers.

Downhole flow regimes in horizontal boreholes can be complex and can include stratification, misting, and recirculation. Water, the heaviest phase, segregates to the bottom of the pipe followed by a mixing layer of dispersed oil bubbles above. Gas, when present, rises to the high side and when all three phases are present, small fluctuations in well inclination changes the flow regime and velocity profiles. For this reason, conventional production logging tools deliver less-than-optimal results in horizontal wells because they were developed for vertical or near-vertical wells where multiphase flow regimes are simpler and more predictable.

The Flow Scanner was specifically designed to address production logging challenges in highly deviated and horizontal wells. With its array of micro-spinners, and electrical and optical probes, the Flow Scanner is able to quantify multi-phase flow in horizontal wells regardless of undulations and corresponding flow profiles.

In this talk case studies will be presented from the Erb West field which is located in East Malaysia. It will be shown how flow profiles were determined and three phase flow was quantified in four horizontal wells. As all four wells were located in different parts of the field, GORs and other production parameters varied considerably from one well to the other. It will be shown how the Flow Scanner results helped optimise production under the diverse conditions of all four wells.

NEAR SURFACE 7

Regolith

THE ROLE OF LANDSCAPE EVOLUTION & HYDROSTRATIGRAPHY IN DRYLAND SALINITY DEVELOPMENT AND CONTROL IN SOUTH-WEST WESTERN AUSTRALIA

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In broad Wheatbelt valley floors of southwest Western Australia, Quaternary alluvial, colluvial and lacustrine deposits may cover Eocene and/or Pliocene sediments up to 70 m thick on basement rocks. Most palaeovalleys have an alluvial sands and gravel aquifer in the base of the palaeochannel itself with lignitic beds trending upwards into confining lacustrine (or shallow marine) clays and finally into the surficial aquifer of sands and clays, where present.

Due to landscape inversion, these sediments appear high in the landscape. From 250 to 230 m AHD the confining clay layer above the palaeochannel sand is characterised by large lakes, including Lake Nunijup in the Kent River catchment, and by swamps, including Darkan Swamp in the Helena River catchment.

The palaeochannel sand aquifer readily discharges saline groundwater where dissected by rivers draining to the south and west coasts. Locally unconfined between the elevations 230 to 200 m AHD, its discharge consequently sustains pools, increases the stream salinity and provides most of the salt load of the Kent River. Discharge to the Helena River sustains year-round saline flow from the same elevation range.

Below 200 m AHD, the rejuvenated rivers have narrow valleys and gain less salt load from the weathered bedrocks. At 200 m, the Kent River changes direction to the south, having cut through the sediment profile to the faults and joints of the basement rocks.

These characteristics invite salt storage mapping to focus on the sedimentary profiles within this elevation range as part of catchment management initiatives to address dryland salinity.

SHALLOW GEOPHYSICAL AND HYROGEOLOGICAL STUDIES TO CHARACTERISE PALAEOCHANNEL PROPERTIES, A CASE STUDY FROM THE TANAMI DESERT, NT

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Palaeochannels are typical geomorphic features representing drainage streams or rivers, which were flowing either during the past time and now stand buried or shifted due to tectonic or geomorphological processes. They often contain considerable thicknesses of sediment with elements which have been dated from the Mesozoic through to the late Cainozoic. These sediments are known to host, or act as pathfinders, to economic mineralisation, and are an important source of potable groundwater, particularly in remote areas. Located about 600 km northwest of Alice Springs, the Tanami region of the Northern Territory is an emerging gold province in Australia. Although not genetically related, some of the gold deposits are located on the margins of palaeochannels. Outcrop in these areas is sparse and bedrock is generally covered by *in situ* and transported regolith materials, that at places may reach more than 300 m. Interest from industry and extensive drilling activity in the region has provided us with a natural laboratory to apply a multi-disciplinary approach for studying regolith properties and processes. As part of the research activities of Co-operative Research Centre for Landscape Environments and Mineral Exploration (CRC-LEME), we have carried out ground transient electromagnetic (TEM) and down-hole EM measurements as well as hydrogeochemical sampling of the open drill holes at the Titania mineral prospect. Apart from identifying possible locations of mineralisation, these studies have clearly delineated the structure of the palaeochannel, the character of the fill and the properties of the groundwater.

HIGH-RESOLUTION AIRBORNE ELECTROMAGNETIC SURVEYING FOR DRYLAND SALINITY MANAGEMENT: THE TOOLIBIN LAKE SKYTEM CASE STUDY, WA

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The SkyTEM airborne EM system has been deployed in Australia since late 2006, and has been flown for a variety of applications including salinity mapping, palaeochannel detection, geological mapping and base metals exploration. Economic geological applications of the system have included gold and uranium exploration, as well as direct detection of massive sulfides. The SkyTEM instrument was designed to produce airborne electromagnetic data of a quality comparable to that which can be obtained from existing ground TEM systems, and is unique in that it can alternately transmit in low-moment, early-time sampling, and high-moment, late-time sampling modes, thus providing a combination of high-resolution shallow information with a maximum depth of exploration comparable to that of other contemporary EM systems. The instrument directly measures parameters crucial to quantitative interpretation of the electromagnetic data, including pitch, roll and altitude of the transmitter and receiver as well as transmitted current.

We demonstrate application of the SkyTEM system to high-resolution palaeochannel mapping at Haddleton Nature Reserve, Western Australia. The SkyTEM data is shown to provide results comparable to those from surface TEM and gravity surveys, but with much improved spatial coverage. Case histories of high-resolution SkyTEM mapping for a range of commodities are also presented.

Day 3: Wednesday 21 November 2007

08:30–10:00

MINERALS 1.8

Crustal/Regional

OPENING UP NEW AREAS FOR EXPLORATION IN QUEENSLAND

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The Queensland Government, through the Department of Mines and Energy, is actively seeking to increase exploration activities in the State. Two dedicated programs: Smart Exploration and Smart Mining – Future Prosperity are running concurrently, aimed at collecting new regional-scale geoscientific data to better define the State's resource potential.

The Smart Exploration program commenced in 2005, with the data acquisition phase, which is now complete. A$10 million has been spent acquiring airborne magnetic, radiometric and gravity data in the Mt Isa region and the Bowen and Surat Basins. Swaths of Hymap Hyperspectral data were also collected in the Mt Isa region.

The Smart Mining – Future Prosperity program commenced in 2006 providing a further A$19 million funding injection for geoscientic data acquisition. Airborne geophysical and gravity surveys are planned for Charters Towers, Cape York and Cooper Basin. In addition, deep-crustal seismic profiles and coincident magnetic-telluric studies have been undertaken in the Mt Isa region to assist predictive mineral discovery. Further Hyperspectral data collection has also been planned along key elements in the Mt Isa, Georgetown Charters Towers and Drummond Basin regions.

At the end of these programs, 75% of Queensland will be covered by airborne magnetic and radiometric data at 400 m line spacing or better, and at least 65% of the State will have gravity readings on a 4 km grid or better.

3D GEOLOGICAL MAPPING AND POTENTIAL FIELD MODELLING OF WEST ARNHEM LAND, NORTHERN TERRITORY

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A regional scale 3D geological map was compiled of the upper crustal sequence in the West Arnhem Land region, Northern Territory, based on surface mapping, limited drilling information, and liberal amounts of geological inference. Modelling of the gravity and magnetic field response of this map was proposed as a means of evaluating the viability of this geological proposition. A relatively good supply of mass density and magnetic property data were available to convert the 3D geological map into property models in preparation for potential field modelling. The presence of numerous relatively thin magnetic horizons, dykes, and sills provided many challenges for producing

geologically-realistic magnetic property models with the chosen regular rectangular mesh element format when trying to reproduce the regional magnetic field observations. Attempts at regional-scale gravity field modelling were far more straight forward and successful. A stochastic geological modelling approach was used to derive a large number of geological maps by making small changes to the highly uncertain interpretive parts of the original 3D geological map. A subset of these derived geological maps had associated mass density models that could adequately reproduce the gravity field observations. The common characteristics of this subset of derived geological maps were isolated using statistical techniques and used to refine our portrayal of the regional scale 3D geological features.

THE BENEFITS OF WIDE LINE SPACED AIRBORNE GRAVITY GRADIOMETRY ON REGIONAL SURVEYS

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To stimulate the development of natural resources most governments maintain a basic national geophysical database to outline regional structural geology and basin geometries. Magnetics and gravity are normally the tools of choice. There is an obvious trade-off between cost and detail, especially in the case of gravity. Airborne gravity gradiometry can be configured to optimise this trade-off.

The advent of gravity gradiometry means that shorter wavelength mass distributions are detectable than what is possible with conventional airborne gravity. However, long wavelengths are also captured on regional gravity gradiometry surveys making it suitable for integration with existing gravity data bases. This will be demonstrated by analysis of several airborne datasets.

An airborne gravity gradiometry survey was conducted in Arnhem Land, Northern Territory, that was previously surveyed by conventional airborne gravity for the NT government. Both surveys were flown with the same survey specifications. Spectral analysis of the 2 km and derived 4 km line spaced data shows that the airborne gravity dataset has limited signal content shorter than 3 to 4 km spatial wavelengths. The gravity gradiometry data on the other hand demonstrates that it can resolve 1 km spatial wavelengths. The analysis indicates that airborne gravity gradiometry offers better resolution at the same line spacing making it the more economic choice in many regional scenarios.

An additional benefit of gravity gradiometry on regional survey programmes is the option to infill areas of interest to capture detail not possible with conventional airborne gravity; This enables more cost effective use of the regional gravity gradiometry data in any exploration program.

MINERALS 2.5

EM

APPLICATION OF A NEW TEM DATA ACQUISITION SYSTEM BASED ON A HTS SQUID MAGNETOMETER (SQUITEM) TO METAL EXPLORATION IN BROKEN HILL AREA

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JOGMEC completed construction of the SQUITEM, a three-channel TEM data acquisition system based on the HTS SQUID magnetometer, in 2006. An HTS SQUID is a high-sensitivity magnetic sensor that has wide bandwidth, and offers high field sensitivity, even at low frequencies. The SQUID magnetometer offers advantages over an induction coil receiver in detecting conductive targets especially in the presence of conductive overburden.

The magnetic field resolution of the SQUITEM is 300 fT/√Hz at 1 kHz as measured in the field. A Slew rate (6.8 mT/sec) is sufficient to respond to square-wave primary-field variation. Frequency bandwidth from DC to 100 kHz provides minimal distortion of the recorded signal.

JOGMEC applied the SQUITEM to minerals exploration at the White Roo Prospect in the Border Project, west of Broken Hill, a JOGMEC/Minotaur Joint Venture. The joint venture was targeting Broken Hill Type Pb–Zn–Ag mineralisation. Initial drilling had intersected pyrrhotite/chalcopyrite mineralisation hosted within a mafic gneiss. A SQUITEM survey was conducted in October 2006 to investigate bedrock conductor highlighted by a conventional TEM survey. The SQUITEM data was superior to the conventional TEM system with respect to depth of investigation. The SQUITEM data profiles and inverted sections highlighted a conductive zone at depth that was not apparent in the conventional TEM data. Drilling of this bedrock conductor resulted in the intersection of pyrrhotite-chalcopyrite mineralisation.

TOTAL FIELD EM FOR HIGHLY CONDUCTIVE TARGETS

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Total field magnetometer sensors, such as those of the optically-pumped cesium vapour variety, are not conventionally used in electrical geophysics. Exceptions to this are Sub-Audio Magnetics (SAM) surveys, carried out with such a sensor typically moving and measuring magnetic fields continuously at sample rates of 1–4 kHz. At the very low base frequencies (often below 1 Hz) used in EM surveys for highly conductive targets in very conductive terrain, cesium vapour magnetometers have an instrument noise level which is superior to almost all sensor types. This is an important issue for the detection and discrimination of highly conductive targets and can accelerate data acquisition.

At the higher frequencies (say 100 Hz and greater) collected during the survey, coil sensors are generally better performers. However, signal-to-noise ratios for a total field survey at these frequencies can be supplemented by modifying the transmitter current waveform to increase signal.

Total field sensors do not need protection from motion during a reading. In some cases data can be collected with the sensor traversing, potentially resulting in a final data set with high spatial resolution. Interpretation of total field EM data is no more difficult than working with vector EM data. In most cases the advantages of superior data quality and logistical simplicity of the total field survey outweigh the loss of magnetic field vector information.

Examples of total field EM data acquisition and processing will be presented, with particular reference to the detection and modelling of highly conductive targets.

PETROLEUM 1.8

Time Lapse

GEOPHYSICAL IMAGING FOR CO_2 MONITORING OF THE OTWAY BASIN PILOT PROJECT

Kevin Dodds[1,2], *Milovan Urosevic*[1,3]*, *Donald Sherlock*[1,2], *Brian Evans*[1,3], *Shoichi Nakanishi*[1,4] *and Anton Kepic*[1,3]
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The Australian Cooperative Research Centre for Greenhouse Gas Technologies (CO_2CRC) has developed a demonstration pilot project for all aspects of geosequestration of CO_2. In preparation for acquiring a time lapse 3DVSP for this project we carried out an extensive series of vertical seismic profiles to assess source performance, operational efficiency, target imaging using a range of zero offset, walkaway, offset source and shear seismic VSPs. We were able to image the target reservoir at 2 km with resolution bandwidth of greater than 140 Hz. Analysis of shear energy in both zero and offset surveys showed the main stress direction consistent with other data. We will review these surveys and the subsequent baseline 3DVSP.We will also review the design of an integrated sampling and geophysical completion for the monitoring well. This completion is configured to provide geochemical sampling at 3 distinct levels, as well as three types of geophysical monitoring activities; an array of geophones centred at 1470 m will be used to acquire walkaway VSP data during injection, a set of three triaxial geophones just above the reservoir will be set to monitor microseismic events, and a set of hydrophones and geophones within the reservoir will be deployed for high resolution travel time measurements.

FUNDAMENTAL SEISMIC PARAMETERS OF INJECTED CO_2

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When CO_2 is injected into a saline aquifer, its flow is controlled by the rock permeability, porosity, chemical composition and fluids, and its state-of-phase; and the reservoir pressure and temperature conditions control its state of phase. Alternatively if pressure is relatively low, it may change the phase from supercritical and form a gas, as at Sleipner Field in the North Sea. So, it is important to understand the state-of-phase of the fluid.

During the injection procedure, CO_2 dissolves in the formation water dependent on the reservoir pressure and temperature conditions, and with time, role of dissolution as a trapping mechanism increases. While monitoring CO_2 as a liquid or gas, it becomes equally important to quantitatively verify both dissolved CO_2 and CO_2 in its gaseous state.

We dissolved CO_2 in pure water and passed it through a variable low pressure cell at room temperature. During this time, ultrasonic transmission tests were conducted to monitor the seismic response with CO_2 in its dissolved and its gaseous phases. It was found that the amplitude of signal was far more sensitive to the amount of dissolved CO_2 than velocity, and it was observed that the transmission amplitudes were a function of the density of the dissolved CO_2 in brine.

These empirical seismic data provide reason to believe that while seismic reflectivity may be used successfully for fluid monitoring, the use of vertical seismic profiling may be a useful method for quantifying fluid in-place, for verification purposes.

PETROLEUM 2.5

Seismic Acquisition Forum

NEAR SURFACE 8

Environmental/Engineering

SOME STUPID SHALLOW SEISMIC EXPERIMENTS I HAVE DONE

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While near-surface and classical seismic explorations obey the same laws of physics, the relative importance of those laws is different for the two types of surveys. These differences have led to some eccentric experiments with unexpected and occasional serendipitous outcomes. Progress attained by our research group has occurred through a mixture of stupid experiments that turned out to be clever and clever experiments that turned out to be stupid. Shallow seismic methods have matured noticeably since the time 25 years ago when the world's scientific literature contained few refereed papers on shallow reflection. Much of the maturation is related to the revolution in microelectronics and the associated several orders of magnitude decrease in computational costs, while developments in sources, seismographs, and field methods have all played a role to differing degrees. However, other driving factors in this improvement have included demonstrable attainment of objectives such as providing structural contour maps of bedrock beneath alluvium, delineating shallow faults, evaluating near-surface stratigraphy to detect preferential groundwater flow paths, and detecting underground cavities. By 1999, we had demonstrated seismic reflection images from depths of less than a metre, easily within reach of a marginally competent grave digger. Detecting such shallow reflectors is expensive, however, because of the requirement to plant geophones at intervals of 10 cm or less. The effective resolution potential of classical seismic exploration data recorded on land is often determined by geologic conditions in the upper few tens of metres; in addition, the majority of statics problems commonly occur in the upper 30 m. We are currently experimenting with methods of making near-surface three-dimensional seismic imaging more cost-effective.

IS IT TIME TO RE-ENGINEER: NEAR-SURFACE SEISMIC REFRACTION METHODS?

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Most current near-surface seismic refraction operations are under-capitalised, they employ inefficient field procedures, and they deliver an outdated low resolution 2D product. In order to generate growth and more widespead use for environmental and geotechnical applications, it will be necessary to modernise the great majority of refraction operations.

The most critical step will be the adoption of 3D methods, which emphasise the superior lateral resolution of geophysical methods, and which generate more detailed geotechnical models of the subsurface. Furthermore, greater use of amplitudes, the other 50% of the data, is recommended to resolve many ambiguities, to generate density models, and to recognise inhomogeneities such as voids. These advances will require more efficient approaches to data processing with full trace methods, such as the refraction convolution section, to handle the greatly increased volumes of 3D data and to image out-of-plane events.

In order to adopt 3D methods it will be essential to develop more efficient methods of data acquisition using roll-through methods with greatly increased numbers of recording channels. This will require many geotechnical organisations to decide whether their core business is data acquisition and processing or the provision of specialist geotechnical services through the interpretation and integration of results.

Most of the technology required to modernise refraction methods already exists. Its adoption is being hindered by an 'engineering culture' which emphasises risk minimisation, the strict adherence to standard procedures, the adoption of codes of practice and the use of 'proven' products, all of which encourage minimum standards rather than innovation and excellence.

GENERAL INTEREST 1

Hyperspectral

CASE STUDY: COMBINING HYPERSPECTRAL IMAGING WITH AIRBORNE GEOPHYSICS FOR MINERAL EXPLORATION

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This paper will present results from the combined use of hyperspectral data with airborne magnetics and radiometrics for mineral exploration in Western Australia. Due to the remoteness of Western Australia, it is often difficult to gain ground access to exploration leases for the initial phase of exploration. Hyperspectral data allows us to map the lithology of rock outcrops, while airborne magnetics enables us to interpret the structures of rock units to depth.

MAPPING REGIONAL ALTERATION PATTERNS USING HYPERSPECTRAL DRILLCORE SCANNER

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Hyperspectral drill core scanning using the CSIRO HyLogger™ between 2002 and 2005 focused on accumulating spectral data from a series of signature holes across South Australia. One component of the software used to process the data provides a summary for each hole indicating the amount of each detected mineral as a percentage of the scanned hole. By converting this percentage into the number of metres of detected mineral present in the drill hole this information can be presented in a GIS

Four mineral suites are coming to the fore in alteration mineral mapping using HyLogger™: aluminium hydroxide white micas, magnesium-iron chlorites, carbonates and iron oxides. Each of these suites can relate to Eh-pH conditions in a mineralising system. For white mica, the transition from muscovite to phengite, as measured by the change in wavelength position of the ~2200 nm absorption feature, represents the progressive depletion of aluminium from the crystal structure with increasing iron or magnesium content. Reflecting Empirical studies show a correlation between concentrations of economic metals and the presence of phengite that may also reflect local fluid pressure conditions. Magnesium and iron chlorites demonstrate a similar partitioning and are often components of the mineralised section. Calcium, iron and magnesium carbonates are a third component. Spectral studies have distinguished between hematite, Fe^{2+} goethite and Fe^{3+} goethite. HyLogger detects in wavelengths appropriate to these suites and software interprets relative abundances. With some 600 holes and 61 000 m of core scanned across South Australia regional patterns are starting to appear.

TOWARDS COAL QUALITY ESTIMATION FROM GEOPHYSICAL LOGS

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Coal density plays an important role in projecting and reconciling coal tonnage and quality variation. The best estimation of coal density is from direct measurement on core, but cored holes are sparse relative to chip holes due to the cost of drilling and subsequent laboratory analyses. All holes are geophysically logged, and if the geophysical data are accurately calibrated against core then they can be used to improve the sampling of spatial variability across a deposit. However, uncertainty about the precision and accuracy of the density estimation from geophysical logs still precludes its use for reserve analysis across the industry at large. A common comment is that 'one accurate data point from laboratory analysis is better than hundreds of inaccurate ones'.

In this paper, we will review the principle of density logging and some potential calibration issues. The laboratory measured coal density data from different mines will be compared with corresponding borehole logging data. We will examine the causes of error and variation in hope to improve correlation and use of geophysical logs in coal quality estimation.

10:30–12:00

MINERALS 1.9

Crustal/Regional

SUB-BASALT IMAGING FROM GRAVITY STUDIES OVER THE DECCAN VOLCANIC PROVINCE OF CENTRAL INDIA

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A large part of the northwest and central India is covered with Cretaceous Deccan volcanic. The presence of a thick sequence of Mesozoic sediments underneath the volcanic cover has opened a new frontier for hydrocarbon exploration. Recently, we have carried out detailed gravity measurements over the Deccan Syneclise of central India as part of a geophysical study to delineate subtrapped Mesozoic sediments.

The Bouguer anomaly map shows a number of significant short wavelength anomalies due to shallow sources superposed on long wavelength regional anomalies due to deep seated sources. Important among these are:

- an E–W trending gravity high associated with the Satpura Mountain Belt, indicating the presence of high density magmatic material at the deeper level,
- a long wavelength gravity low in the southern part, which bears an inverse correlation with topography of the Ajanta Hills, indicating mass deficiency beneath the excess topography load due to isostatic compensation, and
- a short wavelength nearly E–W trending gravity low suggesting the presence sediments beneath the volcanic cover.

The residual gravity field reveals a number of circular positive anomalies due to alkaline intrusives apart from short wavelength negative anomalies aligned east–west probably due to sediments. Modelling of the residual gravity field constrained by other geophysical information has brought out prominent subtrapped Mesozoic sub-basins along the Tapti rift. It is observed that sediment thickness increases towards the east reaching a maximum of about 2.0 km. It is therefore inferred that the Deccan Syneclise region of central India has a large potential for hydrocarbon exploration.

POTENTIAL FIELD 'WORMS' AND MODELS AS THE BASIS OF A 3D TECTONIC MODEL OF THE KOONENBERRY BELT, NORTH-WESTERN NSW

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Completion of a 1 : 100 000 geological mapping program over the Koonenberry region of north-western New South Wales has allowed the Geological Survey of NSW to develop techniques for potential field modelling of serial, sheet-by-sheet cross-sections, with the ultimate aim of constructing a 3D interpretative tectonic model for this Delamerian margin. Modelling has been aided by comparison of magnetic and gravity structural trends, revealed by edge analysis of upwardly continued fields ('worming'), made practical by improved data density and quality resulting from the *Exploration NSW* initiative. Worms aid modelling in two senses: indirectly, through qualitative assessment of tectonic styles; and directly, by fixing the position and trend of otherwise poorly imaged deep sources to constrain inversion. We exploit the different rate of decrease during upward continuation of anomalies due to dipole (magnetic) and monopole (gravity) sources, to distinguish structural differences between relatively shallow (<2–5 km) and deeper rocks. This has been particularly useful for examining the fold-and-thrust tectonics of the region and for investigating the deep roots of intrusions.

Resulting structural models, based on a combined geophysical and geological interpretation, reveal a series of features related to repeated late Neoproterozoic to Cambrian rifting, amalgamation of the Delamerian and Thomson orogens, and subsequent sinistral transpression. Pre-existing structures within the two orogens serve to localise deformation and intrusion during the transpressional stage, in a feature termed the Cobham Kink Zone. An enigmatic large remanence anomaly related to the Cobham Kink Zone awaits interpretation.

'WORMING' IN NEW SOUTH WALES

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Traditional interpretations of potential field data usually require the interpreter to trace boundary lines on an anomaly map between bodies with sharply contrasting petrophysical properties. These contrasts may represent sharp discontinuities or interfaces between geological features such as faults, stratigraphic contacts, and the sutures of intrusions. Because of the non-unique solution of potential field data, the same map can be viewed differently depending on the interpreter. To reduce this ambiguity, we use a relatively new and robust technique based on Multiscale Wavelet Edge Detection analysis ('worms') to trace the gradients in potential field data. Worms are lines produced by multiscale wavelet edge analysis of upward continuations of potential field data and they indicate both the surface trace and subsurface dip of major breaks in the geology, including faults. Strings of points are created at the maxima of the total horizontal gradient grids for many upward continuations. The higher the continuation level (long wavelength signals), the deeper the structure represented by the worm.

The surface geology of many areas of NSW is very poorly known and geologists rely on geophysical interpretation to extrapolate the surface geology at depth. Multiscale edge detection analysis has been applied to gravity and magnetic data in regional NSW, and their interpretation has been valuable in better integrating and understanding of the geology, tectonics and mineral systems. We present examples of interpretations in the Cobar Project area and the Koonenberry/Thomson in the far west of NSW. Interpretations of other parts of the state are underway.

MINERALS 2.6

Electrical

LOOKING INSIDE PORES: POLARISATION BY CONSTRICTIVITY OF PORES

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Two slow types of induced polarisation (IP), namely electrode and membrane polarisation, are known and accepted worldwide. It is also assumed by many geophysicists that the IP processes at time on and time off are the same and that there is a linear dependence between the applied electrical current and the IP amplitude. However, the results of laboratory measurements very often show the opposite.

There is another less known and less developed type induced polarisation: polarisation by constrictivity of pores. This type of polarisation occurs in sediments containing pores with different surface areas in which the mobilities of ions and transfer numbers are different. Mathematical modelling of the IP effect was done for simple and complex pore structures. When electrical current flows through a channel containing pores with different radii (transfer numbers), an excess/loss of ions accumulates at the boundaries. The duration of the polarisation process in pores is controlled by the transfer numbers, radii of the connected pores and amplitude of the electrical current. If a large pore connects to a narrow pore, the ion concentration in the vicinity of the contact decreases and the current flows up to time t_0 when the electrical circuit ruptures and the potential difference between the pore ends becomes constant. The blockage of pore channels controls the electrical resistivity of sediments. It was shown that the processes of IP are different at time off and time on due to different boundary conditions and that there is not a linear dependence between applied electrical current and IP amplitude. A new algorithm allows for the mathematical modelling of complex combinations of pore structures. This can be applied to the interpretation of the IP method and physical modelling of petrophysical properties of sediments.

SIX YEARS EXPERIENCE WITH OFFSET POLE–DIPOLE AND OTHER 3D IP ARRAYS

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It is now more than six years since the initial tests of pole–dipole IP that led to the development of the offset pole–dipole array were carried out at Copper Hill in NSW. In this period, the authors have been involved in more than 50 similar surveys world-wide including a complete resurvey of the Copper Hill prospect using a more advanced 'production' style configuration.

Numerous practical lessons have been learnt through the progress of these surveys. Different methods of electrode emplacement, array geometry and electrode types have been evaluated both in the field and through modelling.

A study of safety considerations led to the recognition of the importance for extremely good ground contact for remote electrodes in pole–dipole surveys, not only to boost the transmitter current but also to lower the electrical potential of the remote wire to avoid fire and shock hazards.

The pitfalls of 3D configurations where the receiver dipole lies close to an equipotential were not widely appreciated in early surveys but it has been found that these can result in spurious anomalies that may be very difficult to evaluate unless the problems are recognised early in the processing.

OPTIMISATION OF ELECTRODE ARRAYS USED IN 2D RESISTIVITY IMAGING SURVEYS

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Four different methods to automatically select the optimal set of array configurations that will give the maximum resolution of the subsurface with 2D electrical imaging surveys with a limited number of measurements were tested. The first method (CR method) directly calculates the model resolution and selects the array configurations that give the maximum model resolution. This method gives the best results but is the slowest. The second (ETH) and third (BGS) methods use linear approximations to estimate the change in the model resolution matrix. The ETH and BGS methods respectively use the first and second power of the sensitivity values in calculating a good function. Both methods are about two orders of magnitude faster than the first method. The ETH method gives poorer results than the BGS method which approaches that of the CR method. The fourth method uses a combination of the BGS and CR methods. It produces results that are almost identical to the first method but it is about an order of magnitude faster. The different methods were tested using data from synthetic models and field surveys. The models obtained from the inversion of the data sets generated by the four different methods confirm that the expected quality of the models.

PETROLEUM 1.9

Time Lapse

USING 4D SEISMIC DATA TO UNDERSTAND PRODUCTION-RELATED CHANGES IN ENFIELD, NWS AUSTRALIA

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The Enfield Oil Field, located in the North West Shelf, Australia, is a Woodside operated field (40% Mitsui interest) that began production in July 2006. The business decision to acquire 4D was to obtain a better understanding of injector pathways, compartmentalisation (both stratigraphic and fault controlled), reservoir pressures and water front movement.

A dedicated baseline survey was acquired in 2004 with very good image quality. The monitor survey, acquired 7 months after production, is the first dedicated 4D monitor survey in Australia. The results achieved very high repeatability levels. Both surveys were processed in parallel to enhance production-related effects.

A series of 4D modelling studies were conducted to decide the criteria for successful 4D interpretation. Pressure and saturation effects were modelled to determine the impact of production-related effects on the 4D. The competing effects of pressure and saturation changes on seismic amplitudes are complex, therefore an additional 3D swath was acquired over a water injector whilst injecting. This approach helped to calibrate pressure and saturation effects and identify preferential pathways within the main producing interval. The rock properties vary across the field with the eastern most area requiring AVO interpretation to determine fluid movement. A 4D AVO inversion was also performed to further support this interpretation.

In this paper we will present the 4D interpretation results using the AVO inversion and seismic and how the results were integrated with production and geological data.

THE ROLE OF ROCK PHYSICS MODELLING FOR THE ENFIELD 4D SEISMIC

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4D seismic feasibility was investigated for the Enfield Oil Field to better understand the reservoir performance. 4D seismic aims at detecting production-related reservoir changes by analysing changes in its seismic signature over time. In order to link static and dynamic reservoir parameters and rock elastic properties a rock physics model is necessary.

The dynamic reservoir models for Enfield predicted large increases in reservoir pressure due to water injection at several locations in the field within the first few months after the start of production. In addition, more slowly expanding saturation changes due to oil production were expected.

One major question to be answered by a rock physics modelling approach was: can the predicted pressures and saturations be seen by 4D seismic after only 8 months of production, i.e., is 4D monitoring feasible? The answer involved correct modelling of the pressure and saturation effects on seismic with respect to expected acquisition noise.

We built a representative rock physics model for the Enfield area based on well logs and core elastic measurements. The rock physics modelling showed that the expected pressure increases will lead to detectable 4D signals and the acquired data proved the modelling right.

In addition to feasibility estimates, rock physics models are needed for quantitative interpretation of the 4D seismic. Once data became available we were able to validate the model against pressure related seismic signatures. Rock physics modelling for various 2D sections helps understanding the reservoir changes observed.

LAND SEISMIC ACQUISITION REPEATABILITY FOR TIME-LAPSE MONITORING OF CO_2 SEQUESTRATION

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Time-lapse surface and borehole seismic surveys are planned for monitoring the injection of CO_2 in the CO_2CRC Otway Project in Victoria. Critical to the success of this is to ensure optimum repeatability of acquisition parameters and ground conditions. In order to assess the relative influences of source types and environmental conditions, a series of repeated test surveys have been undertaken.

The study utilised repeated high-resolution seismic surveys along the same 2D line. The first test line was acquired with mini-vibroseis (6000 lb) in wet conditions when the top soil and the weathered layers were fully saturated. The line was subsequently re-recorded in dry conditions where we utilised the same mini-vibrator, but in addition repeated the line using a free-fall weight drop. Both sources have similar total energy output but a vibrator is a controlled frequency source while a weight drop is not. Despite differences in the signal generated by these two sources, almost identical stacked sections were obtained after phase matching and scaling of the two datasets. Far greater differences were observed between the two vibroseis lines recorded at different times of the year (wet and dry periods).

Our results clearly demonstrate that near surface conditions has a first order effect on repeatability of land seismic surveys. A common belief that deployment of the same seismic source and positioning errors are crucial for successful time-lapse seismic needs to be re-examined in light of our results, which show that these factors are of secondary importance for land seismic surveys.

PETROLEUM 2.6

Seismic Acquisition Forum

CONTINUAL IMPROVEMENT IN THE MANAGEMENT OF HEALTH, SAFETY AND ENVIRONMENT IN SEISMIC ACQUISITION

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The management of Health and Safety in the Petroleum Industry has seen many significant changes since the introduction of the Safety Case Regime after the Piper Alpha tragedy. Environmental legislation in Australia has also undergone significant changes since the introduction of the Petroleum (Submerged Lands) Act, Management of Environment Regulations, 1999 and the Environment Protection Biodiversity Conservation Act, 1999.

As the Safety Case principles do not apply to seismic operations, the responsibility for the management of Health and Safety for seismic vessels in Commonwealth Waters falls under the jurisdiction of the Australian Maritime Safety Authority (AMSA). The environmental aspects of marine seismic acquisition are managed by the State Designated Authorities and the Department of Environment and Water Resources in Canberra.

The effective management of Health, Safety and Environment in seismic operations cannot be achieved by the Government Authorities and the Operators of Petroleum Titles alone. The integration and commitment of the seismic acquisition contractors to achieving the HSE goals of the Government, the Operator and their own organisation is the key to achieving successful HSE outcomes.

The responsibilities of HSE management are shared between Government, Operators and Contractors, but the accountability rests solely with the Operators. In the paper, some of the challenges currently faced in marine seismic acquisition are discussed and a process explained which establishes clear accountabilities, ensures active engagement of contractors and provides a consistent program to eliminate health, safety and environmental incidents in seismic operations.

NEAR SURFACE 9

Environmental/Engineering

3D SEISMIC REFLECTION SURVEY DESIGN AND MODELLING AT THE BEENYUP WASTE WATER TREATMENT SITE, WESTERN AUSTRALIA

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In Perth, Western Australia, there has been both an increasing demand for water and decreasing rainfall over recent years. Managed Aquifer Recharge is a water recycling method identified as having the potential to reduce pressure on Western Australia's surface and ground resources. For this reason a treated waste water injection trial is planned for the Beenyup Waste Water Treatment plant. The treatment plant is located in the northern Perth suburb of Craigie. The trial will include detailed hydraulic flow and reactive transport modelling of the injected water. Accurate modelling requires precise knowledge of the hydrostratigraphy below the injection site. Consequently a high resolution 3D seismic reflection survey will be used to assist in building a detailed groundwater flow model. Optimal 3D survey geometry has been designed based on a preliminary 2D survey, VSP data and the resolution required for the target injection zone within the Leederville formation. 3D survey design was faced with various difficulties as it needed to be designed with a number of exclusions zones related to topographic mounds, vegetation and existing infrastructure. Future construction plans at the site were also factored in to allow for future time lapse seismic surveys after long term injection has pressurised the target aquifer. Forward models of the expected seismic response of the injection process are computed using borehole information and velocity-pressure tests from core sample tests.

HIGH RESOLUTION SEISMIC SURVEY OF THE PROPOSED BEENYUP WASTEWATER INJECTION SITE

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The Beenyup waterwater treatment plant is situated in close proximity to residential properties approximately 20 km north of the central business district of Perth, Western Australia. It is proposed that treated wastewater from the plant will be injected into the sub-surface in preference to releasing it to the ocean. In order for this to occur over a long period of time a good understanding of the connectivity of the sub-surface aquifers in the vicinity of the injection site is required.

High resolution surface seismic together with VSP data were collected at the site using a high-power impact source. The resulting sub-surface images will provide valuable input to a regional sub-surface flow model and the preliminary results are encouraging. This paper describes the acquisition and processing techniques used in the experimental seismic survey.

HIGH RESOLUTION SEISMIC REFLECTION AND RADAR FOR HYDROGEOLOGY: THE GNANGARA MOUND, PERTH BASIN, WESTERN AUSTRALIA

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A comprehensive geophysical program has been carried out with the overall objective of resolving hydraulic properties and boundaries below the Gnangara mound. Initial results have been highly encouraging. Radar transects, more than 15 km in length, reveal up to three shallow potentially 'water retentive' layers above the regional water table for the superficial aquifer. Both shallow sedimentation such as buried dunes and post deposition layering can be readily interpreted over large areas from the radar data. Interpretation of the radar data is assisting in developing a large scale infiltration distribution models for the Gnangara Mound. The high resolution seismic reflection surveys aim to resolve hydrostratigraphy from surface to 1500 m depth. Of particular interest is large scale hydraulic separation between Perth's major aquifers, which include the Superficial, Leederville and Yarragadee. Previous seismic surveys in this area produced low-resolution discontinuous events that could not be used for such purposes. Recently we acquired high-resolution seismic profiles using our telemetric system and a high-power impact source. High CMP fold combined with careful target oriented data processing produced quality images. These enable interpretation of up to 20 layers including several unconformities in the top 1500 m. Further advance in acquisition, particularly application of high-power, high-frequency seismic sources and data processing are hoped to enable routine application of reflection seismic methods in hydrogeology. Results from the seismic reflection and radar surveys will feed into the PRAMS hydraulic flow model for the Perth Basin.

GENERAL INTEREST 2

Potential Fields/Seismic

INFLUENCE OF SELF-DEMAGNETISATION EFFECT ON DATA INTERPRETATION IN STRONGLY MAGNETIC ENVIRONMENTS

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It is commonly accepted that adequate knowledge of true magnetisation direction of a causative body is crucial in order to accurately interpret magnetic data by quantitative methods such as inversion. Most currently available algorithms require the knowledge of magnetisation direction, since it is an essential piece of information for carrying out the forward modelling. Such a requirement has been the driving force for development of many well recognised approaches for estimating total magnetisation when strong remanence or self-demagnetisation are present. Example problems to which these methods are commonly applied include, but are not limited to, the interpretation of magnetic data over banded iron formations, nickel deposits, kimberlite pipes, and depth to basement problems.

In this paper, we discuss the influence of the self-demagnetisation effect on magnetic data and present an alternative means of quantitatively interpreting such data in highly magnetic environments. In particular, we present two important results based on simulation which one might consider in their interpretation of magnetic data when self-demagnetisation is present. First, current methods for estimating total magnetisation, which are typically applied to the problem of remanent magnetisation, do not reliably recover this parameter when the anomalous source bodies have high magnetic susceptibilities. And second, a single value estimation of total magnetisation does not provide adequate information to properly resolve subsurface geology through inversion. Numerical experiments demonstrate that directly inverting amplitude data, calculated from magnetic data yet weakly dependent on magnetisation direction, produces superior results when interpreting data generated in terrain with high magnetic susceptibilities.

AUTOMATIC ANALYSIS OF AEROMAGNETIC IMAGES FOR GOLD EXPLORATION

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An automatic image processing technique is developed for the quantitative prospectivity analysis of Archaean lode gold deposits. It is based solely on aeromagnetic data and does not require knowledge of the location of existing deposits. Instead, the aeromagnetic expressions of what are perceived to be geologically significant characteristics are sought within the aeromagnetic data. Gold mineralisation is known to occur near major crustal breaks manifesting as large-scale shear zones; which act as conduits for mineralising fluids. Mineralisation occurs in regions of structural complexity adjacent to the shear zones. Progressing towards the automatic detection of such regions, we find the regions of magnetic discontinuity that are related to shear zones and lithological boundaries, then identify prospective regions nearby using the following three stages. The first step is to perform texture analysis using an entropy measure to represent the randomness of local texture. Regional scale discontinuities will have a consistent magnetic response which will be laterally continuous. The second step finds the regions of discontinuity by detecting bilateral symmetric features from the texture analysis output. The final stage involves analysing nearby regions of magnetic discontinuity using a 2D fractal surface analysis technique to search for areas with complex magnetic responses. A preliminary experiment was conducted using aeromagnetic data from the Yilgarn Craton in Western Australia and the regions selected by the proposed system contained over 76% of all known deposit locations and 82% of the greater than 1 tonne-deposit locations.

A NEW ALGORITHM FOR THE SEISMO-ELECTROKINETIC EFFECT GENERATED BY DIFFERENT SEISMIC WAVES AND ITS APPLICATION IN A SMALL AREA

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A new approach to model the Seismo-ElectroKinetic Effect (SEKE) is presented. It is based on the principle that at a specific time, each point on a wave front that travels through a medium exerts equal pressure on both the solid matrix and the pore spaces. Consequently, the basis for the calculation of the SEKE is described by two fundamental equations. The first equation describes the relative displacement of sedimentary particles at arrivals of the seismic wave and the second equation describes the transient streaming potential, induced in a pore, when the pressure pulse is applied to a pore.

Calculation of the SEKE on the surface requires the following steps:

- Calculate the pressure gradient in a single pore caused by a seismic wave,
- Transfer the EKE arising from the single pore to the porous media,
- Integrate the SEKE signals from the space or layers and
- Calculate and access the Electro kinetic coefficients.

A new algorithm has been developed and used for the interpretation of SEKE field data. The main purpose was to establish the relevance of the SEKE method, and to compare it to other well established geophysical methods. Several other geophysical methods were applied along a profile: Resistivity (DC), shallow refraction seismics, magnetic gradiometry, electric self-potential and frequency domain electromagnetics (FDEM). Each method contributed towards the solution of this problem. The seismic technique provided depths and thicknesses of layers. The results obtained by the DC resistivity show that high resolution can be obtained by this method. The magnetic gradiometry, self-potential and FDEM methods must be regarded as supplementary methods to obtain additional information about depth and structures in the basement material. The results of the SEKE soundings indicated ground water at shallow depths.

13:00–14:30

MINERALS 1.10

Crustal/Regional

INNOVATIVE IMAGERY, DATA QUALITY CONTROLS, STATE-WIDE GRID MERGES

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The NSW Department of Primary Industries (NSW DPI) recently acquired 200 000 line-km of high-resolution airborne geophysical data over the far north-west and far south-west of NSW. This completed the high-resolution coverage of the western half of NSW. We will describe the processes used by NSW DPI in monitoring the data quality, which resulted in contractors delivering data to a very high standard.

Upon release of the new data, it was timely to update the state-wide grids for TMI and radioelement data. We will describe the daunting processes and difficulties associated with preparation for stitching approximately 40 survey grids for TMI and K, Th & U. Grids were checked for compatibility, correct coordinate system and appropriate survey overlap before they were manipulated and 'feathered' together. The merging process was complex and required large amounts of RAM and disk space. Regional magnetic offsets were encountered along the boundaries between surveys with large and short wavelength responses. The process resulted in a 2.13 Gb 50 m grid for TMI and a 348 Mb 100 m grid for each radioelement channel.

The presentation will show a novel approach by NSW DPI in interpreting aeromagnetic data in the poorly outcropping areas of the 1 : 25 000 geological maps of the Broken Hill region. A most useful image includes contours of TMI 2VD and flight path draped over a combined colour image of TMI with a grey-tone image of TMI 2VD. The resulting image highlights near-surface features and complements/extends geological mapping. It permits precise location of magnetic features and delineates magnetic domains.

COMBINING PASSIVE AND ACTIVE SEISMIC DATA IN UNDERSTANDING THE TERRANE STRUCTURE OF THE EASTERN GOLDFIELDS, WESTERN AUSTRALIA

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A recent, near-comprehensive, passive seismic survey of the variations in crustal structure across the Yilgarn and Pilbara cratons has shown significant contrasts in seismic structure between neighbouring terranes/superterranes. The Eastern Goldfields showed a unique variability in crustal structure in agreement with a recent reinterpretation of terrane boundaries within the Yilgarn craton. We further investigate the Eastern Goldfields region using a 3-way approach which combines conventional passive seismic analysis with innovative seismic noise-correlation methods and constraints from active source data. The conventional passive seismic analysis enables the receiver function S-velocity structure, and hence composition, of the lower crust to be constrained. The noise-correlation analysis allows seismic structure in the 5–15 km depth range to be determined and provides medium resolution coverage across regions not previously explored using active seismic methods. Where active source data have been acquired, shallow structure and deeper seismic velocity determinations are added, providing an unprecedented combination of seismic constraints on the structure of this complex and economically important region. We find that, although some individual terrane boundaries within the new Eastern Goldfields reinterpretation are open to question, the concept of the multi-terrane amalgamation is substantially justified by the exceptional variability of the lower crustal structure. Upper crustal structure is often characterised by seismic discontinuities which may represent detachment surfaces or layered structure that varies between terranes over a sub-100 km length scale. The accretionary history of the superterrane and associated regional tectonic setting of numerous formations of economic significance would now appear to be beyond question.

MINERALS 2.7

Potential Fields

THE AMPLITUDE/PHASE TREATMENT OF FULL TENSOR GRADIOMETRY

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For each observation of the potential field full tensor gradient, a rotation from world coordinates to principal components space is made. The two independent gradient magnitudes together with a succinct 'quaternion' representation of the rotation is termed the amplitude/phase representation of the signal.

This separation of concern isolates aspects that are invariant to rotation from the coordinate system. Benefits that flow from this approach are many and include:

(1) Full tensor gridding from observed profiles is achieved using SLERP techniques (spherical linear extrapolation). Model studies show this method to correctly estimate intermediate tensors.
(2) Applications of the technique to the Frequency Method also show required abilities to deliver low pass filtered data.
(3) Just 3 independent power spectra are derived using this approach.

This contrasts with the previous 'best' practice of 5 power spectra and 15 cross spectra. Obviously this previous practice mixed the rotational and signal strengths aspects. Practical applications allow the treatment of the full tensor gradient as the signal, maintaining

all the correct properties. Visualisation and interpretation aspects of this signal are illustrated.

AAGD07: A NEW ABSOLUTE DATUM FOR AUSTRALIAN GRAVITY AND NEW STANDARDS FOR THE AUSTRALIAN NATIONAL GRAVITY DATABASE

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The datum and scale for gravity surveys conducted in Australia is provided by the Australian Fundamental Gravity Network (AFGN). The AFGN consists of about 950 stations at over 250 locations and was initially established in the early 1950s. Until recently, all of these stations were established using relative gravimeters to measure gravity differences between stations. The errors in these measurements were distributed by least squares adjustments of the network.

Relative ties to overseas gravity stations were used to establish the datum prior to the establishment of the Isogal84 datum in 1984. The Isogal84 datum was constrained by ties to five absolute gravity sites established in Australia by a Soviet absolute gravimeter in 1979.

Geoscience Australia has conducted absolute gravity measurements with a portable absolute gravimeter at 60 AFGN stations. These measurements show that the Isogal84 datum is 78 microgals (1 microgal = 1×10^{-8} m/s^2) higher than the absolute measurements. A new datum, the Australian Absolute Gravity Datum 2007 (AAGD07), has been defined based on these absolute gravity measurements and the AFGN and the Australian National Gravity Database (ANGD) have been adjusted to this new datum.

Concurrent with implementing AAGD07, the formulae used for reducing gravity data in the ANGD have been reviewed and updated. These changes include using the 1980 International Gravity Formula, ellipsoidal heights, and a spherical cap bouguer correction that accounts for the Earth's curvature. These new formulae will provide more accurate anomalies, particularly in longer wavelengths for regional studies.

COMMERCIAL GRAVITY OPERATIONS – MODERN GPS SURVEYING AND DIGITAL GRAVITY METERS

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Gravity surveying has been available since the early 1900s in the form of analogue gravity meters, barometric levelling and conventional optical line of sight surveying methods. The gravity method was more generally used for applications in the oil industry.

With the advent of GPS technology in the form of centimetre accuracy from GPS surveying methods, commercial gravity operations developed. Line of sight surveying methods were no longer required and gravity meters became digital, easier and more reliable to use.

Commercial gravity surveys are now undertaken on a routine basis from projects spanning hundreds of kilometres for mapping large sedimentary basins to very small localised engineering projects covering merely hundreds of metres.

This paper outlines the development of the GPS surveying technology and the digital gravity meter. The integration of the two technologies is discussed with respect to the development of the commercial gravity survey method. Several applications and case studies are described with specific examples given from various international gravity contractors.

PETROLEUM 1.10

Crustal/Regional

A DEEP SEISMIC REFLECTION SURVEY OF THE GREAT SUMATRA EARTHQUAKE ZONE USING ADVANCED SEISMIC TECHNOLOGY

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Following the 9.3 magnitude earthquake offshore Sumatra and the devastating associated tsunami of 26th December 2004, the SAGER research consortium was formed. As part of a series of planned geophysical experiments, 950 km of 2D deep crustal seismic reflection data was acquired in July 2006 by the vessel M/v Geco Searcher in the vicinity of the earth quake epicentre. The survey design, data acquisition, processing and resultant images are discussed.

The data were recorded with a reconfigured, modern recording system. Several modifications were made to the overall data acquisition system in contrast to its normal use for oil and gas seismic exploration. Pre-survey modelling and design studies led to a final acquisition configuration including very large volume, deep towed sources, deep towed single sensor cables, with up to 12 km offset and 20 s recording time. Separation and preservation of very low frequency signal from noise was critical to the success of creating the deep structural image. Multiple reflections and velocity determination also proved to be a big challenge in this data.

The processed images show that the subduction zone can be observed to a depth of over 40 km, along with the associated shallower faults. The interpretation of these data and integration with other geophysical measurements is continuing.

This is a rare example of a reconfigured, modern, large scale, commercial seismic reflection system being employed for successful academic deep crustal research.

CRUSTAL THICKNESS IN AUSTRALIA: WHERE, HOW AND WHAT FOR?

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The most reliable estimates of crustal thickness come from refraction and wide-angle reflection seismic experiments. As of 2007, there are ~400 such measurements in Australia, both

onshore and offshore. Crustal thickness onshore varies from 30 (Pilbara Craton) to 60 km (Mount Isa Inlier). In the continental margin, the crustal thickness gradually reduces from ~35 km onshore to ~10 km at the continent-ocean transition zone. In some cases the continent-ocean boundary is marked by the disappearance of granite-type seismic velocities (~6.1–6.2 km/s) from the velocity profile of the crust, but in recent years there was an increased number of instances where lower seismic velocities in the upper crust (~5.1–5.5 km/s) were not unambiguous indicators of oceanic crust. Latest additions to Australian crustal thickness data are from onshore-offshore experiments in southwest Australia, and ocean-bottom seismograph recordings in the Exmouth Plateau and Cuvier Margin. Crustal thickness data are essential for several geological tasks including estimation of heat production for hydrocarbon maturation modelling. Estimates of relative significance of depth of subsidence, heat production in the crust, and thickness of the crust for positioning of hydrocarbon maturation windows show that variation in subsidence may have a relatively minor effect. The effects of crustal thickness are 1.4–3.4 times greater for equal percentage variation. These estimates allow the requirements for accuracy of the underlying measurements to be determined. An accuracy of ±0.5 km for crustal thickness is required to position the base of dry gas maturity window with ±50 m accuracy.

USING AIRBORNE GRAVITY DATA TO BETTER DEFINE THE 3D LIMESTONE DISTRIBUTION AT THE BWATA GAS FIELD, PAPUA NEW GUINEA

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As part of an appraisal program by InterOil of the Bwata gas reservoir and prior to undertaking further 2D seismic surveying, a preliminary 3D geology model of the geological setting was rapidly built using Geomodeller.

The 3D geological structural model was built using a single 2D seismic line, well data from the Bwata-1 and Triceratops-1 wells, surface geological data and airborne gravity data. Eight cross sections across the Bwata Anticline were created from surface geology, seismic and well data in 2D Move. These sections were imported into 3D Geomodeller. A 3D model was then created and the forward gravity response computed. Areas where the observed curvature of the gravity differed from the predicted indicated that the 3D geology needed adjustment.

The airborne gravity data was observed at a mean height of 1200 m. Density variations from general background of 2.25 g/cc are provided by the Cretaceous Ieru Formation at 2.40 ± 0.05 g/cc and the Puri and Mendi limestone at 2.65 ± 0.05 g/cc.

The outcome of this study was the prediction of the geological setting and the extent and thickness of the limestone beds. It is interpreted that two NE/SW near vertical faults connect with a network of low dip faults through the limestone. Also some overthrusting of the limestone is proposed to explain the density anomalies associated with the gas field. The extent and thickness of the limestone were quickly constrained using the vertical derivative of the gravity.

PETROLEUM 2.7

Acquisition

SEISMIC ACQUISITION AND ANALYSIS OF THE ELK CARBONATE RESERVOIR, PAPUA NEW GUINEA

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With the discovery at Elk1 in 2006 InterOil has embarked on a reservoir appraisal and delineation program. This program includes acquiring new 2D seismic data to complement and enhance data which was acquired in 2005 and 2006. That exploration 2D seismic data confirmed structural closure of the limestone reservoir however the narrow bandwidth and resulting low seismic resolution hindered detailed reservoir analysis. The 2007 2D seismic appraisal program was designed to generate better quality 2D data enabling the use of more advanced reservoir analysis. Prior to acquisition commencing on the 2007 program various array designs were modelled and parameter test were undertaken to optimise the acquisition parameters and measurably increase the data quality. The initial results are encouraging, indicating sufficient data quality for sequence stratigraphic studies.

Due to the paucity of well data in the Elk prospect, generation of resource estimates based on a static 3D reservoir model is guided by seismic data which will enable the inter-well space to be populated with reservoir properties. This process will be enabled by robust well to seismic correlation from the planned simultaneous surface and sub-surface seismic acquisition along with zero-offset VSP data. With well constrained correlation, the wireline logs can be more confidently upscaled to seismic resolution and seismic inversion performed on the 2D dataset.

To further increase confidence in the data used in the inversion process and to understand fluids in the reservoir, AVO analysis will be performed on the new seismic dataset calibrated with the wireline logs from the area.

THE CONTRIBUTION OF GEOPHYSICAL SURVEYS TO AUSTRALIA'S ONSHORE ENERGY SECURITY PROGRAM

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In 2006 the Australian Government announced new funding for an Energy Security Initiative. Geoscience Australia (GA) has subsequently implemented an Onshore Energy Security Program (OESP) to identify Australia's onshore energy resources. As part of this program, GA will be acquiring (under contract) airborne magnetic, radiometric, and electromagnetic (EM) survey data, as well as ground-based gravity data across Australia for the next four years. The geophysical survey data will provide essential pre-competitive information to stimulate exploration for Australia's uranium, thorium, geothermal and on-shore petroleum resources.

Airborne radiometric data are an essential component for the assessment of uranium and thorium resources. However, the

usefulness of Australia's National Radiometric Database is limited by the fact that the individual surveys comprising the database are not all registered to the same radioelement datum, and it is thus difficult to compare data between surveys. GA is currently acquiring 140 000 km of magnetic and radiometric tie-lines across Australia. These will be used to level the National Radiometric Database surveys to a common datum, as well as to recover intermediate wavelengths in the National Magnetic Database that are currently corrupt. These magnetic wavelengths (100–400 km) are important for the evaluation of energy resources.

The demand for resources, and increased funding by the Commonwealth, States and Territories, have been the driving factors in the recent improvement in the regional geophysical coverage of Australia. Over 2.5 million line-km of airborne survey data and 100 000 new gravity stations have been added to the National Airborne Geophysical Database in recent years. These data are giving explorers new insights into Australia's minerals and energy potential.

WIDE AZIMUTH TOWED STREAMER: APPLICATIONS FOR EXPLORATION AS WELL AS DEVELOPMENT

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Marine 3D wide-azimuth towed streamer acquisition methods have provided significant improvements in seismic imaging of deep water sub-salt reservoirs in the Gulf of Mexico. The initial surveys were designed to provide very dense trace sampling and illumination under the salt.

Subsequent to these successful field-specific surveys, wide-azimuth acquisition designs have been developed to allow cost effective use of the technique over large areas for exploration objectives. This paper will describe a 'sparse' acquisition configuration that has been derived from the source/receiver geometry used on the Mad Dog survey for BP. This design allows a full suite of data densities from the initial first pass for the exploration objectives to successively appended additional data acquired through the appraisal and management phases of field development.

In addition, initial results from wide azimuth and multi-azimuth surveys have shown significant improvements in attenuation of multiples and scattered noise, not just improvements in sub-salt imaging. The scale of this S/N improvement will be modelled for fast velocity geological environments such as carbonates to demonstrate that these benefits may also apply in a wider range of basins than first thought. In turn, this improvement, together with the wide range of azimuths recorded, allows azimuthal anisotropy to be estimated thus leading to possible identification of fracture patterns in fractured carbonate reservoirs.

NEAR SURFACE 10

Environmental and Groundwater

GEOSCIENCE, WATER AND SALINITY IN RURAL TOWNS OF WESTERN AUSTRALIA

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Western Australia has serious salinity problems both in the agricultural lands of the WA Wheatbelt and also in the rural towns which serve the Wheatbelt. A major multi-disciplinary, multi-agency project: Rural Towns – Liquid Assets began in mid 2005 to address salinity and water issues in sixteen of the most salt affected towns. Salinity affects the infrastructure (roads, railways, buildings) and also affects the water supply. The project is designed to mitigate the effects of salinity, find more water for these towns and more uses for the water to encourage new industries. The project includes social surveys, economics, geoscience, hydrogeology, and engineering design work and implementation. Geophysics is being used to provide information on the geology of regolith and bedrock. Gravity has been widely used in this project and has proved to be very useful. This is supplemented by other geophysical methods such as time domain electromagnetics, seismic and borehole geophysics. In each town the scientific questions to be answered are defined and appropriate geophysical programs are designed to answer these questions. This paper includes examples of work done to provide understanding of the geology and hydrogeology in project towns and how this fits in with the total project.

JOINING THE DOTS: HOW AIRBORNE GEOPHYSICS HELPS CONSTRAIN HYDROGEOLOGICAL MODELS

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Hydrogeological models rely on accurate conceptualisations of groundwater flow in the sub-surface. For this we require an accurate interpretation of the sub-surface, regolith, architecture and definition of preferential lines, and obstacles to, movement of water. Traditionally, this information is acquired through judicious use of groundwater bores, combined with expert knowledge and assumptions based on the understanding of the regions hydrogeology. Flow nets are created from water level data and flow parameters determined from point determinations through pump tests.

Increasingly, geophysics is being used to help define the sub-surface architecture, identify preferential flow lines and constrain the extents of groundwater models. In particular, airborne geophysics (AG) can provide a contiguous image of subsurface features, defined by the technology being used. Thus, airborne magnetics can define pre-existing, buried river channels from the relict iron oxides on some river gravels; airborne electromagnetics (AEM) can define the preferential flow-lines from the higher conductivity of water saturated sediments.

Field mapping and careful calibration of signals is imperative, though this is often an iterative process requiring additional information from new bore holes or cross-comparisons with other technologies.

Examples of where AG technologies have greatly aided the development of groundwater models will be shown from regions in South Australia. Both simple (flowtube), and complex (modflow), models have been enhanced by using AG data.

GENERAL INTEREST 3

Earthquakes and Seismicity

CONJOINT USE OF H/V SPECTRUM RATIO AND SPAC METHODS TO ASSESS 2D EFFECTS OVER THE TAMAR VALLEY IN LAUNCESTON, TASMANIA, AUSTRALIA

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The Tamar rift valley runs through the city of Launceston, in Tasmania. Damage has occurred to buildings in the city due to earthquake activity in the Bass Strait. The presence of the ancient valley, filled with soft sediments of varying thickness over short distance, is thought to induce 2D resonance, amplifying the surface motion over the valley. We conjointly use horizontal to vertical spectral ratio (H/V), and spatially averaged coherency (SPAC) microtremor (passive seismic) survey methods to identify and characterise 2D effects over the Tamar valley. When recorded on profiles across the valley, H/V data provide qualitative information on the variation of the valley's physical properties. Variation observed in the H/V peak frequency with distance on two profiles across Tamar valley correlates well with the known shape of the valley.

Array measurements at seven selected sites, analysed by SPAC, give a precise estimation of the shear wave velocity profile with depth. SPAC arrays located in Launceston CBD have good resolving power of the shear wave velocity and thickness of sediments. Sediments thickness and velocity vary significantly over the city. The top layer is composed of 1 m to 15 m of very soft Quaternary sediments, with a velocity ranging from 50 m/s to 150 m/s. Tertiary sediments fill the Tamar valley, and have a thickness varying between 10 m and 250 m. S-wave velocities of these sediments range from 400 m/s to 750 m/s.

Modelling of wave propagation using layered earth approximation allows comparison of field data acquired over real 2D geology with theoretical 1D model.

AN ACTIVE FAULT IN SOUTHERN TAIWAN DETECTED USING SHALLOW SEISMICS AND GROUND PENETRATION RADAR

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We conducted high-resolution shallow seismic exploration and ground penetrating radar (GPR) exploration to assess the earthquake hazard along the speculated north-south striking Chaujou Fault that is along the mountain foot at the western edge of the Central Range in the southern tip of Taiwan. Shallow seismic and GPR survey lines are approximately east-west oriented, perpendicular to the speculated fault. All these survey lines run across the speculated fault. A fault plane of an 50° east-dipping angle is interpreted using shallow seismic profiles and one GPR profile. The interpreted fault locations are consistent with the scarp on the earth's surface with an error of only a few metres, indicating that the scarp marks the Chaujou Fault's surface location. The GPR profile even shows fault planes within a few meters depth, indicating fault rupturing within the past centuries. As Taiwan has humid climate with high erosion and deposition rate, these evidences imply that the Chaujou Fault really exists and is an active fault, that it has been displaced within the past centuries, and that it is a potential earthquake-inducing mechanism.

SEISMICITY IN NORTHERN WESTERN AUSTRALIA

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A new seismic monitoring network installed in northern Western Australia in October 2005 seeks to record low-level seismicity in the region, with a view to understanding event frequency, magnitude, location, geological controls on seismicity and deep-crustal structure that may be contributing to crustal weakness. Data from a network of eight semi-permanent stations, located at localities between Shark Bay and the Dampier area, complements data from an additional 80 stations that were deployed for shorter periods as part of other research projects at the ANU between 2000 and 2006. This dense network of seismometers provides the opportunity for a detailed analysis of seismicity and shallow- and deep-crustal structure in the northwest of WA.

For events such as the M5.3 event in Shark Bay in February 2007, our network provided the detailed data required for accurate location and potential fault plane solutions. Potential fault plane orientations have significant implications for our understanding of the neotectonic evolution of this part of Australia, and mechanical contrasts in the crust that may be predisposing areas to failure. Despite the region hosting large earthquakes (Geraldton, 1885, M6.5; offshore WA, M6.2, 1920), including Australia's largest known event (Meeberrie, M7.3, 1941), little is known about the frequency, magnitude or causes of seismicity in this region, which is far less known than the SW Seismic Zone.

This project is part of an Australian Research Council Linkage project hosted at The University of Western Australia and involving collaboration with The Australian National University and Geoscience Australia, sponsored by Woodside Energy.

15:00–16:00

MINERALS 1.11

Crustal/Regional

CONSTRAINING THE FAR-FIELD STRESS STATE NEAR A DEEP SOUTH AFRICAN GOLD MINE

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As mining activities around the world move deeper underground, understanding the pre-existing stress state and how the mining might perturb it become increasingly important for mine safety. As part of the Natural Earthquake Laboratory in South African Mines

(NELSAM) project, we are investigating the far-field in-situ stress state and mining-induced stress perturbations surrounding the TauTona gold mine in Western Deep Levels, South Africa. The perturbation of the *in situ* stresses by mining activities creates a complex stress field that induces seismicity on a variety of pre-existing (and previously dormant) faults. Knowledge of the unperturbed far-field stress state is critical to understanding what causes the pre-existing faults to be reactivated. We used a combination of near-field observations of drilling-induced borehole failures and slip induced on faults to model the far-field stress state. We used borehole camera data to observe drilling-induced borehole failures (breakouts and tensile fractures) in several short boreholes within the mining region, and a 418 m long sub-horizontal borehole that extends into the far-field. Based on these observations and the results from boundary element modelling, our stress model indicates a normal faulting regime in the far-field with a near-vertical direction a maximum principal stress and a NNW-SSE direction of maximum horizontal stress. This model is consistent with induced slip observed on faults within the mine and localised stress perturbations (manifest as breakout rotations) observed in the camera logs. We use this stress field to predict locations where the stress concentrations associated with mine excavations tend to induce slip on pre-existing faults.

THE NEW TANAMI 3D MODEL – INCORPORATING THE RESULTS OF THE 2005 TANAMI SEISMIC SURVEY

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A new 3D model of the Tanami region has been constructed based on the results of the 2005 Tanami Seismic Collaborative Research Project. The interpreted seismic data consist of four regional traverses that were tested by gravity modelling. The model incorporates the whole of the crust from the surface down to the mantle. Results include an interpreted suture between the Tanami and northern Arunta regions that was active prior to the deposition of the Tanami Group. The model was produced using 3D GeoModeller, a new mathematically based modelling package that constructs 3D volumetric models based on geological information.

MINERALS 2.8

Potential Fields

NEW DEVELOPMENTS IN GRAVITY APPLICATIONS AND INSTRUMENTS

Chris Nind[1]*, *Tim Niebauer*[2], *Jeff Macqueen*[2], *Derek Van Westrum*[2], *Fred Klopping*[2], *Daniel Aliod*[2] *and Ethan Mann*[2]
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Gravity meters are commonly used to map spatial changes in the earth's gravity, achieving resolution of parts per billion on microgravity surveys. The application of gravity surveys to monitor change and recent improvements in gravity instrumentation will be summarised.

The use of gravity to track the progress of a waterflood in Prudhoe Bay, Alaska, provides a 4D Gravity case history. The surface gravity change caused by the injection of water into the gas cap is measured annually and compared to the expected change calculated from the reservoir model. 4D Gravity provides an effective 'early warning system' for injection and sequestration projects.

A recent borehole gravity survey in Hanford, Washington, demonstrates the ability to measure bulk densities using a borehole gravimeter. The applications include geotechnical studies at waste disposal sites, bridges and structures, locating and monitoring thief zones in reservoirs, and grade control in iron mines. A new borehole gravity meter will be introduced during 2008 that can be used in smaller, inclined boreholes.

Earth tides and other long period movements of the earth can be recorded by suitably configured gravity meters. The ground shaking in Luxembourg before and after 13 January 2007, earthquake in Japan was recorded on a long period seismometer, a superconducting gravity meter and a new portable gPhone gravity meter. The match between the seismometer data and the gPhone data during the earthquake is excellent. The relatively inexpensive portable gPhone gravity meter provides the means to record earth movements along active fault zones and other critical locations.

DEPTH ESTIMATION USING THE MAGNETIC POWER SPECTRUM

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A generalisation of the Spector-Grant method of obtaining depth of magnetic bodies from the power spectrum is demonstrated. The ironstone ore bodies on Tennant Creek are clearly located by the technique and depths are obtained which conform very well to the mineral occurrences database (MODAT). Aside from locating most of the abandoned goldmines on Tennant Creek Map, the technique also identifies many similar anomalies which have not been registered as mined or drilled. To aid explorers who wish to investigate further, a database of positions and inferred depths will be made available. A favourable comparison with the Euler technique for dipoles indicates its usefulness. Limited success is obtained by attempting to map the surface of the basalt flow in the north-west of the map.

PETROLEUM 1.11

Rock Properties

EVALUATION OF TAR DEPOSITS USING NEUTRON TOMOGRAPHY, CANNING BASIN, WESTERN AUSTRALIA

Mike Middleton[1]*, *Frikkie de Beer*[2], *Peter Haines*[3] *and Arthur Mory*[3]
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Tar or bitumen deposits in the Canning Basin, Western Australia are a good indication of the previous presence of petroleum. Preliminary results applying neutron tomography to biodegraded tar sand samples from a mineral exploration hole adjacent to the

Fenton Fault on the southern margin of the Fitzroy Trough demonstrate the value of the technique in investigating hydrocarbon movement in this petroleum system. Neutron tomography allows the imaging of materials with hydrogen-rich components, such as tar and bitumen as 'tomographic slices' because neutrons are attenuated at much higher levels in tar than the matrix.

Pasminco BW26 contains tar deposits in a fault zone in the Ordovician–Silurian Carribuddy Group and a shallower sandstone in the mid-Devonian Worral Formation. The deeper zone is intensely brecciated with carbonate fragments suspended within a matrix of tar. Neutron tomography shows that tar comprises up to 80% of the total rock volume, thereby providing an indication of the original hydrocarbon saturation and implying that the fault zone was a migration conduit. The shallower zone shows selective layering of tar filled bands and calcite veining, which appears to post-date the petroleum charge: possibly the carbonate fluids cooked the original oil deposit to form the tar.

The distribution of tar next to the southern margin of the Fitzroy Trough, as shown by neutron tomography, indicates that hydrocarbons were introduced into the Worral Formation along a deep fault zone. The high concentrations in the fault zone imply significant overpressure driving the petroleum upward, but pore pressure resistance in Worral Formation sandstones prevented all the charge from migrating farther.

NEUTRON IMAGING IN SOUTH AFRICA ADDS VALUE TO GEOSCIENCES AND PETROPHYSICS

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The utilisation of high flux neutron beams for radiography and tomography imaging purposes is limited due to the availability of imaging facilities at nuclear research reactors or spallation sources and also the availability thereof. Currently only two operational neutron radiography facilities in the Southern Hemisphere (one in South Africa and the other in Brazil) are available to be exploited by researchers.

The application of neutrons as an imaging tool depends on the penetration capability of neutrons through dense material. The value of utilising neutrons in the technique is enhanced in the imaging of hydrocarbons or water inside the dense matrixes because of the high attenuation of hydrogen. Neutron imaging is thus complimented by X-ray imaging since X-rays has the ability to penetrate light elements easily while being strongly attenuated by dense material.

The methodology and principle of neutron radiation imaging (including radiography and tomography) applied to the earth sciences, will be discussed by means of several case studies ranging from properties of porous rock to quantitative analysis of the sandstone containing tar. New developments at NECSA regarding the accessibility and utilisation of instruments and facilities at the South African National Center for Radiography and Tomography (SANCRAT) will also be outlined.

NEAR SURFACE 11

Cavity and Karst Detection

CHARTERS TOWERS SHARP PROJECT – ASSESSMENT OF GROUND PENETRATING RADAR FOR THE LOCATION AND RISK ANALYSIS OF ABANDONED MINE SHAFTS

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Charters Towers was once one of Australia's most productive gold fields peaking with an annual production of 319 572 ounces in 1899. The mining was predominantly underground and went as deep as 2000 ft extending under much of the city. Mining came to an end in 1922 with many mine shafts capped with tree trunks and fill. The legacy of this period of activity is as many as 1000 deep shafts with the capacity to collapse at short notice. The Queensland Department of Mines and Energy is currently responsible for the location and capping of the shafts in the Charters Towers Shaft Repair Program (CTSHARP). In 2006 the CTSHARP project team decided to trial Ground Penetrating Radar as a method for locating mine shafts and categorising the risk collapse within small targeted areas. Many of these sites were located in the yards and gardens of private dwellings, horse paddocks and even currently trafficked streets. This provided a wide variety of surface and subsurface materials and site conditions in which to trial the technique. Twenty sites were investigated and in the majority of the sites subsurface reflections were recorded that were indicative of either shaft locations or material collapsing into a shaft. The GPR data was used to both accurately plot the shaft location and give the anomaly a rating of 1–5 with 5 being the highest potential for collapse. The GPR investigation results have been verified by ground truthing and an actual collapse during the heavy rains early in 2007.

GEOPHYSICAL CHARACTERISATION OF VARIABLE LIMESTONE TERRAINS

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Karstic limestone terrains have the potential to cause significant geotechnical risk for infrastructure development, particularly in the Perth environs where large cavities, pinnacles and limestone hardcap have all been found. One of the principal risks is differential settlement of foundations located over variable material. The scale of karstic features can be as small as tens of centimetres for features such as pinnacles or extent over tens of metres for some of the larger cavities (such as Jewel Cave in Yanchep National Park). Geoforce applied a combination of Ground Penetrating Radar (GPR), Electrical Resistivity Imaging (ERI) and Multi-channel Analysis of Surface Waves (MASW) methods to two sites in the Australian Marine Complex in Henderson, on the coast south of the Perth CBD. The surveys were closely tied to previous Cone Penetrometer Tests (CPTs) and the resulting geophysical interpretation provided a 3D volume of the karstic units present, including sands, limestone rock-head, zones of pinnacled limestone and gravelly fill from previous earthworks. No indication of cavities was found in the geophysical data. This information was used to provide a detailed geotechnical classification of the site and to optimise the earthworks required prior to development of the land.

GENERAL INTEREST 4

Earthquakes and Seismicity

A UNIFIED COMPILATION OF ANOMALIES IN PLATE TECTONICS

Ojas Mahapatra, Shivaraman Ramaswamy, Shamsudeen and M. Ponnavaikko*
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This paper is basically a compilation of various anomalies and loop-holes in plate tectonic theory. The tectonic theory explains that earthquakes take place due to tectonic plate movement. Rhetorical questions are raised in opposition to the very basic principles of the tectonic theory and evidences are provided as to why the thin plate theory is implausible. Further evidences opposing crucial concepts such as continental drift theory, seafloor spreading and oceanic floor aging, subduction and emphasising contradiction between data and tectonic model predictions are presented as a part of a preliminary study on Plate Tectonic theory.

The paper is a study of the concepts of Plate Tectonics and its ability to effectively deal with earthquake occurrences. There has been organised opposition about the theory called plate tectonics throughout the world. This paper tries to bring out the comparative study between pros and cons of plate tectonics and contains original calculations as well.

The paper tries to bring out the facts and figures about plates, its occurrence and leads to another research where the earthquake can actually be negated.

A FRESH INSIGHT INTO EARTHQUAKE OCCURRENCES

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Earthquake a phenomenon, thought to be out of control of human is no longer an uncontrolled menace. This paper deals with the cause and effects of earthquakes and its subsequent negation. The shakes and tremors were thought to have been caused by plate movements and related occurrences. We have presented an alternate hypothesis for these phenomena. Our hypothesis is competitive enough to convincingly deal with the anomalies, which are present in the plate tectonic and subordinate theories.

Day 4: Thursday 22 November 2007

08:30–10:00

MINERALS 1.12

AEM

AIRBORNE ELECTROMAGNETIC SYSTEMS

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AEM systems are essential tools for a wide range of mineral exploration and geological or environmental mapping applications. Noise levels in AEM have been lowered with electronic and processing advances, to the point that external noise and suspension (rotation in earth's magnetic field) noise are the dominant remaining sources. There is still however a need and opportunity for improvements in noise reduction. The most challenging development required of AEM is the development of systems operating at 5 Hz or less to penetrate conductive cover and assist in the discrimination of very conductive copper/nickel sulfide deposits. The product of peak dipole moment and the Liu waveform factor provides a quantitative estimate of the effective signal strength of a TEM system at a specific base frequency. To achieve the 5 Hz goal, optimum waveforms and significant dipole moment increases are likely to be necessary.

Altimeter errors and attitude changes provide the main limitations in the depth resolution of shallow, quasi-layered environmental targets. 2D and 3D imaging and inversion strategies are not yet robust or fast enough for routine application, although they are starting to be applied to data. It is crucial that such algorithms account for the lateral smoothing effects of filtering on local anomalies. As the nature of this filtering is often proprietary, and not usually disclosed be contractors, the smoothing effects on data can lead to errors in modelling and inversion that affect direct drilling.

SPECTREM$_{2000}$ AEM AS A MAPPING AND DISCOVERY SYSTEM

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Spectrem Air Limited is jointly owned by Anglo American and De Beers. The Spectrem$_{2000}$ system was upgraded to its current configuration in 2000, with significantly improved transmitter and acquisition capabilities. Since then there has been a steady progression of improvements to the acquisition and receiver components.

The Spectrem design philosophy was to build a broadband system with the following capabilities:

- High resolution mapping
- Deep penetration
- Ability to operate in conductive terrane
- Direct detection
- Safe operation

The aircraft is a Basler DC 3 with twin Pratt and Whitney PT 6 turboprop engines, and a gas turbine generator to produce a RMS dipole moment of 420 000 Am^2. A towed magnetometer and on-board Exploranium crystals allow total field magnetic and radiometric data to be acquired together with EM data. EM survey data is processed in real time using STEP response so that data quality can be assessed directly in flight. EM data can be supplied within 24 hours for gridding and preliminary assessment.

To date over 800 000 km of survey have been flown in Africa, South America, North America and Europe. Due to Spectrem's unique broadband configuration, it has been successful in both direct detection and mapping roles. Recent developments have been aimed at improving the ability to conduct AEM surveys in conductive areas. This includes building a low frequency EM bird and processing developments to obtain better discrimination for more conductive targets.

A number of case studies from various terranes are presented demonstrating the multi-faceted nature of the Spectrem system.

GEOMETRICAL CONSTRAINTS FOR THE DETECTION OF PERFECT CONDUCTORS

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Large, high grade sulfide ore bodies have long time constants rendering them invisible to the off-time of airborne transient electromagnetic (TEM) systems, and have a response only in the on-time. While frequency domain systems are able to detect these economic targets, the small dipole moment limits their investigation depth. To obtain the on-time response of TEM systems, the primary field must first be removed. This requires very precise knowledge of the relative positions of the transmitter and receiver, as well the transmitter orientation. Using GPS measurements, the transmitter and receiver positions can be recorded, allowing calculation and removal of the primary field. Increasing the transmitter-receiver separation greatly reduces the required accuracy of the system geometry. With current GPS measurement accuracies there is a 200 m minimum and 400 m optimum separation for the detection of a small perfect conductor. Thus the on-time response can be determined. A survey was conducted over a known target in a resistive host in Ontario, Canada. A high-accuracy GPS system was placed on the VTEM transmitter and on an AFMAG receiver towed by a separate helicopter trailing the transmitter. We will present results from this field test, and show that very conductive targets can be successfully detected.

PETROLEUM 1.12

Anisotropy/Multicomponent

ANISOTROPIC PP AND PS_V PRE-STACK DEPTH MIGRATION OF 4C SEISMIC DATA: PAMBERI, TRINIDAD

Tony Johns[1]*, *Carmen Vito*[1] *and Raul Sarmiento*[2]
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In 2004, EOG Resources acquired an OBC 4-component swath survey across the Pamberi-1 well location in the Columbus Basin, offshore Trinidad. The motivation from EOG was because a previously acquired conventional 3D towed-streamer survey failed to adequately image the potential reservoir under the main fault. Details of the PP and PS_V processing of this dataset through anisotropic PrSTM were previously described by Johns *et al.* (2006), in which it was demonstrated there existed a qualitative correlation between derived parameters and attributes from P and S_V anisotropic migration velocities, overpressure and known regional geology. This observation was quite remarkable considering that only a limited effort to validate/constrain the parameters was performed. Under the 'Future work' section of the previous publication, it was suggested that further data quality enhancement in preparation for more quantitative rock property classification could only be achieved after pre-stack depth imaging. In this paper, we present precisely that next phase in the 4C processing, advancing the PP and PS_V data through anisotropic pre-stack depth migration. The Pamberi-1 well was used to constrain the anisotropy in the shallow section, with the deeper spatial trend guided by the anisotropy derived previously in the time processing with further updates from detailed event registration. Prior to the depth tomography, the nature of birefringence from the presence of azimuthal anisotropy was first examined to assess its potential impact on the radial PS signal. The shear splitting analysis revealed polarisation alignment with the regional stress direction delineated by fault blocks acting as pressure seals.

APPLICATIONS OF NON-RIGID-MATCHING TO 3D CONVERTED-WAVE (PS) IMAGING

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Processing limitations in the time domain to accurately ray trace, or meticulously model, the full waveform expression of converted wave moveout in the presence of lateral heterogeneity and polar anisotropy often culminate in imaging discrepancies between different azimuth sectors of a 3D converted wave (PS_V) seismic data volume. To compensate for lateral or temporal divergence of converted wave imaging as a function of azimuth, a two-tiered workflow for applying a Non Rigid Matching (NRM) algorithm is applied to combine two distinct 3D azimuth sectors of a PS_V pre-stack time migration (PrSTM) dataset to form a final enhanced 3D PS_V volume with superior stack response and continuity. The method allows for the crossline artifacts from the effect of azimuthal anisotropy on the converted wave moveout to be almost completely removed. Furthermore, the severe acquisition footprint, from insufficient crossline aperture as a result of a sub-optimum survey design, is effectively mitigated. Seismic data examples of 3D inlines, crosslines and time slices taken from a typical 3D/4C survey acquired from the Gulf-of-Mexico and processed in 2006, demonstrate the compelling benefits of the NRM application and the robustness of the developed work flow. Finally, the output NRM displacement attributes (voxel time shift values) are found to possess a qualitative value which are not only powerful indicators of azimuthal anisotropy, but also through calibration, may yield valuable information on the magnitude of shear splitting and principal directions of polarisation.

FRACTURE-INDUCED ANISOTROPY IN SAND RESERVOIRS

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I will present a methodology to calculate fracture-induced anisotropy (FIA) in sand reservoirs. I will assume a set of aligned vertical fractures in an otherwise isotropic rock mass, comprising an HTI medium – a medium with transverse isotropy with a horizontal axis of symmetry, causing azimuthal anisotropy. FIA can be expressed in terms of some geometrical aspects of fractures such as fracture porosity and aspect ratio. It can be also shown as the sum of rock background isotropic compliance and excess compliance as functions of rock elastic properties. I will compute

FIA firstly for dry frame sandstones of the Nelson Field and the Rotliegend Field then include the effect of fluid saturation on anisotropy parameters, by considering the elastic stiffness matrix of a fractured rock in terms of two dimensionless scalar parameters e_N and e_T, representing measures of the overall crack compliance of the fractured rock as functions of the crack porosity and response factors b_N and b_T. It is sown that fracture-induced anisotropy can be of moderate to large magnitude. I will also illustrate near-offset and far-offset compressional- and shear-wave reflectivities for varying azimuth in the Top Nelson oil-sand and Nelson oil–water contact. Compressional-wave AVO attributes such as gradient and curvature of the corresponding scenarios are also discussed.

10:30–12:00

MINERALS 1.13

AEM

ANALYSING FREQUENCY-DOMAIN EM DATA FOR HIGHLY CONDUCTIVE TARGETS

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A RESOLVE data set flown initially for kimberlite exploration has been re-analysed for nickel sulfides. As the latter are highly conductive, the standard processing products such as apparent resistivity grids, deemed useful for mapping kimberlites, did not provide the optimum resolution for data analysis. The survey area is characterised by strong magnetic and EM responses due to the presence of banded-iron formations and pyrrhotite-rich massive sulfides. In order to determine the strongest conductors, time-constants were derived from the RESOLVE survey data. The time-constants are derived from the quadrature and inphase responses at two different frequencies. Due to the strong magnetic response, the RESOLVE data had to be corrected for magnetic permeability before the time-constant computation. This was achieved by inverting the data for a conductive and magnetically permeable layered-earth, followed by a forward calculation of the EM response for a non-magnetic earth. The derived time-constants do not exceed values above 0.5 ms which reflects the conductance aperture of the RESOLVE system. A comparison with plate models shows a close correlation between time constants and plate conductances, with conductances not exceeding 200 S. conductors with conductances/time constants above 200 S/0.5 ms are detectable, but not resolvable.

CALIBRATION OF TIME DOMAIN AEM SYSTEMS USING A GROUND LOOP

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By using a closed, accurately laid out and surveyed multi-turn, insulated ground loop of known inductance L and resistance R, we can analytically calculate and predict the response of any time domain AEM system. By measuring the current induced in the ground loop, we have tested a two-stage calibration process whereby a system check is made on the transmitter-ground loop coupling and another is made on the ground loop-receiver coupling. Furthermore, in resistive terrain, the ground loop response provides an excellent way to directly measure the dB/dt field of the transmitter.

Using this method we analyse the predicted and measured responses of several AEM systems. In every case, the predicted and measured responses differ. Agreement between measured currents and the prediction can be achieved by solving for errors in: (a) the altitude of the system, (b) the lateral position along the line compared to the GPS reference, (c) system tilts. The final but necessary step to achieve a fit to received data required a prediction of the averaging effects of proprietary noise-reduction filters on the predicted response. The method provides a cost-effective way to calibrate time domain AEM systems, and to highlight problems such as transmitter current, receiver window timing and gain.

MEASURING THE WAVEFORM OF TIME DOMAIN AEM SYSTEMS USING A GROUND LOOP

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Measurement of the current waveform of time domain AEM systems which possess coincident-loop receivers can be problematic due to the high moment of the transmitter loop during the on-time. We present a simple method of measuring the transmitter current waveform by measuring the current induced in a closed, accurately laid out and surveyed multi-turn, insulated ground loop of known inductance L and resistance R. The current induced in the ground loop, measured by a 24-bit A/D converter capable of sampling at 96 kHz, is the convolution of the time derivative of the transmitter current waveform with an exponential decay of time constant equal to the L/R ratio of the wire loop. With an understanding of the A/D converter measuring the ground loop response, the transmitter waveform can be deconvolved from the ground loop decay.

PETROLEUM 1.13

Anisotropy/Multicomponent

ANALYSIS OF CONVERTED REFRACTIONS FOR SHEAR STATICS AND NEAR-SURFACE CHARACTERISATION

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In certain situations, a richer geological interpretation can be achieved through integrated P- and S-wave seismic imaging. Converted-wave reflection is an economical methodology for such integrated analysis. However, one of the major impediments to viable onshore converted-wave imagery is that S-wave receiver statics are difficult to estimate. This is because near-surface S velocities are much lower, and often more variable, than P velocities.

Refraction statics is a standard deterministic approach to conventional (P-wave) statics analysis. In this paper, we examine an extension whereby S-wave statics are estimated via analysis of PPS refraction arrivals. These are refracted waves which convert from P to S for the up-going, head-wave section.

Since these PPS refractions are not first arrivals, their identification and analysis is more challenging than for standard P-wave refraction. For our real-data trials, we have combined modified time-depth and delay-time algorithms. The latter is needed when reversed refraction data are not available.

The derived PPS refraction statics have a similar short-wavelength character to S-statics obtained via a specialised residual-statics analysis of converted-wave reflections. The long-wavelength characters are different. Based on standard P-wave practice, we believe that an optimal production approach will include converted-refraction analysis, followed by converted-wave residual statics.

Although the thrust of this work is towards derivation of S-wave statics, an interesting auxiliary output is also available. Based on theoretical modelling, the S-to-P time-depth ratios can be tuned to provide P-to-S velocity ratios (and hence dynamic Poisson's ratios) for the near-surface. This has interesting implications for lithological and rock-strength analyses in the mining, engineering, and environmental contexts.

POLARISATION ANALYSIS OF OCEAN BOTTOM 3C SENSOR DATA

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In this paper, we analyse vector fidelity of direct P and reflected PS arrivals from multicomponent ocean bottom (OB) data, by mapping apparent polarisation as a function of azimuth and angle of incidence at the seabed. This demonstrates vector fidelity of seabed sensors at its root, i.e., as the amount of distortion of the incoming wave's polarisation. We compare data from a cable system with data from nodes, as well as buried and unburied cable sensors.

As expected, nodes show overall best vector fidelity. For OB cable data, on the other hand, buried sensors show significantly better vector fidelity than unburied sensors, both for downgoing direct P-waves and upgoing PS reflected waves. While both buried and unburied cable sensors exhibit vector infidelity to some degree in the direction along the cable, unburied sensors show in addition poor fidelity in the crossline direction. Vector infidelity of the unburied sensors may be misinterpreted as azimuthal anisotropy with a symmetry axis parallel to the cable.

13:00–14:30

MINERALS 1.14

AEM

AIRBORNE MEASUREMENTS OF NATURAL SOURCE EM INDUCTION RESPONSES TO STUDY SHALLOW SURSURFACE FEATURES – RESULTS FROM 3D NUMERICAL CALCULATIONS

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Major difficulties associated with airborne geophysical surveys are rapidly disappearing with the development of precise positional systems. These techniques could be useful in observing the natural source EM inductive field from a moving airborne platform. Recent studies show that fluxgate magnetometers with high sensitivity along with real-time precise positioning techniques could be used in making such airborne measurements. The concept of airborne measurement of natural source EM induction is similar to the ground based geomagnetic depth sounding (GDS). The only difference is that instead of simultaneously observing the magnetic field with an array of ground stations, airborne system is flown over an area of interest and measures a range of high frequency signals at a pre-defined interval. The 3-component fluxgate magnetometer data thus collected could be processed using the GDS method to study the lateral conductivity variations within the subsurface. The depth from which the information is returned depends on the frequency (or periodicity) selected and subsurface conductivity situations. This method could therefore be successful applied to exploration in cratonic areas (e.g. Canadian Plateau) where there are lots of fresh rock exposures. However it is uncertain how successful this method could be applied in areas of thick regolith cover such as in Australian conditions. Numerical modelling could possibly test the likely success of this method under those conditions. In this paper I shall discuss how one can utilise the 3D Finite Difference forward modelling approach to compute the airborne responses of shallow subsurface lateral conductivity anomalies under various surface/subsurface conditions.

BATHYMETRY AND SEDIMENT DEPTH INVESTIGATION IN BROKEN BAY USING A PROTOTYPE AEM TIME DOMAIN SYSTEM (SEATEM)

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The use of airborne electromagnetic (AEM) methods for measuring water depth and estimating sediment thickness has been demonstrated using commercial AEM equipment that is not optimised for marine surveying. A new prototype helicopter time domain AEM system, SeaTEM(0), is under development for bathymetric surveying. The first sea trial of the SeaTEM(0) system took place over Broken Bay, NSW, in shallow water up to ~30 m in depth. The SeaTEM(0) system was untested and the Broken Bay survey identified instrumentation problems that will be addressed in future surveys. Broken Bay was chosen because the separate paleodrainage systems for the Hawkesbury River, Brisbane Waters and Pittwater which join in Broken Bay give rise to paleo-valleys infilled with unconsolidated sediments, ranging in thickness between 0 m (exposed bedrock) and ~140 m. The AEM survey also included North Palm Beach. Sediment thickness and water depth is predicted from stitched 1D inversion of SeaTEM(0) data based on a simplified two-layer model that represents seawater and sediment overlying a resistive half-space basement (bedrock). The inverted bathymetric profiles show good agreement to within approximately ±1 m with known water depths in areas less than 20 m deep. The inverted depth profile of the second (sediment) layer is noisy; however, the profile clearly follows the depth to bedrock estimated from marine seismic studies down to depths of ~80 m in 30 m water depth. These results show that airborne EM sensors can detect coarse topographic features of deep paleochannels in coastal regions.

A NEW HELICOPTER TIME DOMAIN AEM SYSTEM FOR SHALLOW SEAWATER GEOPHYSICAL SURVEYING – STATIC TRIALS

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A new helicopter time domain AEM system (seaTEM) is under development for bathymetric surveying in shallow waters. Commercial helicopter AEM systems are often operated in areas of rugged terrain and may not be fitted with bird attitude sensors, and altimetry sensors that operate over seawater. SeaTEM is being designed for surveying at lower altitudes than that typical of AEM systems used for mineral exploration and will incorporate inertial navigation and marine-altimetry sensors. SeaTEM is being developed over three years. the first phase involved a series of static (i.e. *non-airborne*) investigations over highly resistive ground followed by a series of static trials over seawater – using a stable non-metallic floating platform ~20 m diameter that permits full scale AEM transmitter-receiver loop systems to be deployed at simulated flight heights of about 20 m above sea level. The static ground investigations involved experimentation to determine the system self response (with and without navigation and altimetry sensors) using different loop conductors and transmitter-receiver coil configurations. AEM hardware was then suspended 20 m above sea level using the floating platform located in calm waters. We present results of the static seawater tests. this approach provides a full-scale AEM system to be 'flight' tested in selected areas of known water depth and sediment type (without the expense of helicopter hire and fuel costs) avoiding electronic interference with helicopter instrumentation and noise caused by bird motion. We believe that this thorough approach will determine an AEM system optimised for bathymetric surveying in shallow coastal waters.

PETROLEUM 1.14

Non-Seismic

CALCULATION OF A DEPTH CORRECTION FACTOR FOR THE S-LAYER DIFFERENTIAL TRANSFORM

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The VTEM system developed and operated by Geotech Limited and Geotech Airborne Limited is a central loop configuration system lending itself perfectly to many traditional ground interpretation strategies. One of these is the S-layer differential transform which is used to generate resistivity-depth sections. An empirical study indicated that delineating conductors in a conductive half space necessitates the implementation of a scale factor in order to obtain the correct depths and conductivity values when applying the S-layer differential transform.

Based on an empirical approach, there was found to be an infinite number of depth correction factors that will still yield acceptable conductivity values and the need arose to explain the origin of this discrepancy and to find the correct depth correction factor. Three possible correction strategies were investigated based on comparison with synthetic data from models which have all shown that depths are overestimated by the S-layer differential transform. The most likely conclusion was that the physical assumptions regarding current distributions made in the S-layer transform lead to poor approximations of the conductors in a conductive half space. Assuming that the equivalent filament for the S-layer behaviour, as with the equivalent filament for the half space behaviour, does not coincide with the electric field maxima in the subsurface led to a plausible depth correction factor which was validated on various synthetic models.

4D REPRESENTATION OF DEEP OCEAN CONTROLLED SOURCE ELECTROMAGNETIC DATA

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Deep ocean controlled source electromagnetic (CSEM) methods in oil and gas exploration have undergone rapid development in recent years. The CSEM transmitter generates coupled vector fields at low frequencies (less than 0.1 Hz) for a large number of transmitter receiver offsets on or close to the Ocean floor. Representation of the distribution and propagation of the transient electromagnetic fields within and below the ocean is of considerably importance to those people engaged in both pure research and the practical applications of electromagnetic methods.

Typically, representation of deep ocean CSEM field data is via simple plots of amplitude and phase versus transmitter offset from each fixed receiver position. However, the reality of EM field propagation in 4D is more fully represented by distributions of rotating vectors for the total and scattering electric and magnetic fields. Methods for 4D representation in stereo projection are provided. The co-location of acquired and model data in the same virtual space imposes additional requirements on the visualisation methods and several examples are provided. The 4D representations are developed in Open Source Mayavi software.

GRAVITY AND MAGNETIC MODELLING OF THE SOUTHERN NORTHLAND BASIN, NEW ZEALAND

Brodie Klue[1]*, *John Cassidy*[1], *Kelly L. Classen*[2], *Donald C. Lawton*[2] *and Corinne A. Locke*[1]
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The Northland Basin, New Zealand, is that part of the greater Taranaki Basin lying mainly offshore and to the west of the Northland Peninsula, covering an area of 120 000 km^2. In the southern part of the Northland Basin (known also as the northern Taranaki Basin), several gravity anomalies with amplitudes of 55–90 mGal, and corresponding magnetic anomalies of 500–1000 nT occur. These anomalies are caused by large volcanic complexes of Miocene age. 2D seismic reflection data show that these volcanic centres are commonly associated with significant structural highs, possibly related to major faulting. The geometries of these volcanic bodies, however, are poorly imaged and lead to ambiguities in interpretation, especially of the pre-Miocene sedimentary horizons and basement, from which

reflections may be masked. A linear magnetic anomaly up to 500 nT in amplitude trends SSW–NNE in the south to NW–SE in the north, following the main structural trends in the region. This feature may reflect the occurrence of a highly magnetic basement terrane, or possibly a relic Cretaceous volcanic arc. Detailed modelling of the gravity and magnetic data has been carried out to constrain the geometry of the volcanic bodies and the depth to basement throughout the basin in order to help resolve some of these ambiguities.

15:00–16:30

MINERALS 1.15

AEM

PROCESSING AND INVERSION OF SKYTEM DATA FOR HIGH RESOLUTION HYDROGEOPHYSICAL SURVEYS

Esben Auken, Joakim Westergard, Anders Vest Christiansen and Kurt Sørensen*
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The SkyTEM system is specially designed for hydrogeophysical surveys with gate times from about 10 μs to 5–10 ms. SkyTEM data does not need any sort of bias correction. To obtain data with a repeatability better than 5%, the data processing and inversion need to take into account a number of parameters.

The SkyTEM system monitors at all times the movement of the transmitter frame in the airspace by measuring GPS position, the altitude and the tilt. In the subsequent data processing the altitude is filtered using recursive filters to remove reflections from tree tops. The tilt is entered to calculate the altitude perpendicular to the ground at the centre of the frame. Also the exact altitude of the receiver coil is calculated along with an area reduction factor compensating for the reduced horizontal area of the coils when they are tilted. Data are filtered using trapezoid formed filters allowing for a small average of the early time gates and a larger average of the late time gates obtaining as small a lateral average as possible. Data are inverted using Constrained Inversion algorithms with a parameterised and/or a smooth model. The forward response include modelling of the full transmitter waveform, low-pass filters in the instrument and a front gate preventing signal to saturate the amplifiers when the current is turned off. Furthermore, the altitude is entered in the inversion as a constrained inversion parameter.

In the presentation we discuss the processing system with respect to obtaining high resolution, reliable and repeatable resistivity images of the subsurface.

HIGH-RESOLUTION NEAR SURFACE AIRBORNE ELECTROMAGNETICS – SKYTEM SURVEY FOR URANIUM EXPLORATION AT PELLS RANGE, WA

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The SkyTEM airborne EM system has been deployed in Australia since late 2006, and has been flown for a variety of applications including salinity mapping, palaeochannel detection, geological mapping and base metals exploration. Economic geological applications of the system have included gold and uranium exploration, as well as direct detection of massive sulfides. The SkyTEM instrument was designed to produce airborne electromagnetic data of a quality comparable to that which can be obtained from existing ground TEM systems, and is unique in that it can alternately transmit in low-moment, early-time sampling, and high-moment, late-time sampling modes, thus providing a combination of high-resolution shallow information with a maximum depth of exploration comparable to that of other contemporary EM systems. The instrument directly measures parameters crucial to quantitative interpretation of the electromagnetic data, including pitch, roll and altitude of the transmitter and receiver as well as transmitted current.

We demonstrate application of the SkyTEM system to high-resolution palaeochannel mapping at Haddleton Nature Reserve, Western Australia. The SkyTEM data is shown to provide results comparable to those from surface TEM and gravity surveys, but with much improved spatial coverage. Case histories of high-resolution SkyTEM mapping for a range of commodities are also presented.

ENHANCING THE RESOLUTION OF THE SUBSURFACE BY JOINT INVERSION OF X- AND Z-COMPONENT SKYTEM DATA

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Numerical modelling shows that the resolution of the subsurface resistivity structures is significantly enhanced if x- and z-component data are inverted jointly. The enhancement is most pronounced in the upper part of the model as the sensitivity kernel for the x-component is more ‘condensed’ compared to the corresponding kernel for the z-component. Best results are obtained if the ground is relatively conductive and therefore the method is best fitted for survey where the average resistivities of the ground are below approximately 100 Ωm, e.g. mapping of saltwater infected layers.

In the field x-component data can be measured with only a few extra costs. However, when the method is simple in theory it is complicated in practice where a number of problems have to be addressed. Tilt of the x- and z-component receiver coils must be measured with an accuracy of better than one degree because even a small tilt adds a significantly amount of z-signal to the x-signal. This ‘contamination’ must be modelled in the forward response of the inversion algorithm and the tilt of the coils must be added as extra (constrained) inversion parameters. It is necessary to low-pass filter the x-component data in order to suppress efficiently the background high frequency noise. Finally the timing of the instrument must be better than 200 nanoseconds to be able to model the first time gate at 11 microseconds.

In the presentation we discuss the method, present a parameter sensitivity study and a field example using SkyTEM data collected at the Toolibin test line, Australia.

PETROLEUM 1.15

Gravity

TARGET DELINEATION USING FULL TENSOR GRAVITY GRADIOMETRY DATA

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FTG Gravity data acquired on airborne and marine platforms measure five independent tensor components that collectively describe a total gravity field. The components capture unique signature patterns related to specific attributes of target geology that when collectively interpreted enable detailed imagery of the target itself in terms of geometry, composition and depth of burial.

The horizontal tensor components Txx, Tyy, Txy, Txz and Tyz are commonly used to identify and map lineaments associated with structural and/or stratigraphic changes or target geometry in a survey area. The vertical tensor component, Tzz, is used to estimate depth and predict compositional information related to target geology. However, these components have traditionally been interpreted separate from one another and often run the risk of missing out on key information.

This paper describes application of a semi-automated approach that combines the individual components into singular representations to best extract the signature pattern common to all components as revealed by the underlying geology. The examples presented are taken from an Air-FTG® survey onshore Brazil to image the structural framework and identify target geology ahead of a seismic programme, and a Marine-FTG®) survey offshore Norway to resolve salt body geometries imaging areas of overhang development.

The resultant interpretation enables the end-user to fast-track the exploration initiative by quickly evaluating target geology for detailed follow-up.

AN INSIGHT INTO THE WALTON BASIN, OFFSHORE JAMAICA: A FALCON® PERSPECTIVE

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A high-resolution, high-definition FALCON® airborne gravity gradiometry and magnetic survey – the largest offshore FALCON® survey to date – was flown during mid-2006 over parts of the Walton Basin offshore Jamaica. This data was acquired as a secondary dataset in 'tandem' with a primary 2D reflection seismic survey. The Walton Basin is a relatively under-explored Early-Tertiary rift basin located near the western margin of the present-day Nicaraguan Rise and forming part of the Chortis Block of the greater Caribbean Plate.

Results from the seismic survey were augmented with historic offshore seismic data, the product of which documented a series of regional events that were successfully mapped across much of the Walton Basin. A number of leads and prospects ranging from Late-Cretaceous to Mid-Miocene in structural and stratigraphic traps have been identified with several prospects hosting multiple targets. Preliminary evaluation of a number of these prospects indicates the potential of multi-billion barrel oil accumulations.

Preliminary interpretations of the FALCON® datasets have allowed confident mapping and correlation of the shallow intra-basinal sediments in addition to the mapping of deeper basement structures and geometries where the seismic resolution is limited. Our integrated approach of employing conventional interpretation methodologies, 2D-forward modelling, 3D-Euler technique and constrained 3-D inversions have shown to be quite definitive in linking the seismic data and the high-resolution potential field data in further understanding the architecture and stratigraphy of the Walton Basin for hydrocarbon prospectivity. The FALCON® data has enabled quantitative assessment of risk with significantly higher confidence than would be afforded by seismic data alone.

CALL TO AUTHORS

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