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SECTION 3
ABSTRACTS

Australian Society of Exploration Geophysicists

PESA Petroleum Exploration Society of Australia

AUSTRALIAN INSTITUTE OF GEOSCIENTISTS

BOLDLY GO...

Bridgeport Energy Limited is an active exploration & production company led by an energetic management team with over 150 years of combined petroleum expertise in Australia and around the world. Bridgeport is a wholly owned subsidiary of New Hope Corporation, a proud Australian resource company.

The company has been operating petroleum exploration, development and production projects in Australia for the past 9 years. With over 160 wells currently under direct management and over 12,000 km2 of high working interest exploration acreage, we are an established operator and explorer in the Cooper-Eromanga and Surat Basins.

Bridgeport is actively looking for interested parties to participate in an exciting exploration program with seismic acquisition and drilling slated for later this year. **For more information about these opportunities please visit our team at the AEGC 2018 Exhibition (booth 39), Sydney International Convention & Exhibition Centre.**

Bridgeport ENERGY
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To learn more about Bridgeport Energy visit www.bridgeport.net.au or email cfink@bridgeport.net.au

Monday 19 February 2018

1040–1220
MONDAY 19 FEBRUARY 2018

1A COAL

COAL IN NSW

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Coal was first recorded in NSW in the late 1790s and first mined in Newcastle in 1799. 85 tons were exported from Newcastle to England in 1805 and today Newcastle is the largest coal export port, shipping approximately 170 million tonnes in 2015–2016, primarily to Asia. Approximately 25 different product specifications of high quality thermal and metallurgical coal are now sold, representing around 80% of the total value of NSW mineral production.

The world class coalfields of NSW were laid down in Gondwana during three periods of coal measure formation. The occurrence of numerous volcanic ash beds (tuffs) throughout these coal measures and the advent of chemical abrasion-isotope dilution thermal ionisation mass spectrometry (CA-IDTIMS) provided the opportunity to acquire a new dataset for use not only in coal geology but in broader basin studies.

CA-IDTIMS has revolutionised U–Pb dating of zircon with a high level of precision and accuracy (less than 100 K for a 255 Ma date). A project commenced in 2010 to accurately determine the ages of tuffaceous sediments of the eastern Australian sedimentary basins. The project, still ongoing, is headed by Geoscience Australia with support from the Geological Survey of NSW, industry and universities.

The project has delivered 146 age dates with more in progress. These data have been used to constrain stratigraphic correlations and sedimentation rates, improve the understanding of basin evolution and permitted an improved calibration of biostratigraphic schemes to the numerical time-scale.

These new age data and advances in the understanding of basin geology can be applied to coal exploration. However, in the context of the current debate about the future of coal and forecasts of an increasing decline in global coal demand – is more exploration needed?

Coal played an important part in the Industrial Revolution. It provided most of the energy for steam engines – a key source of industrial power. Coal was also a key manufacturing material, enabling the economic production of large volumes of iron and steel.

The term ‘Renewable Energy Revolution’ is increasingly used to describe the transition of the global energy mix from a reliance on fossil fuels to a mix based on renewable energy. Just as in the Industrial Revolution, coal will play an important role in a successful transition. Coal is still a key material in the manufacture of iron and steel – crucial to the entire supply chain of renewable energy infrastructure – from the mining of the raw materials to the delivery of finished wind turbines, solar panels and battery storage. Coal will continue to be an important source of base load power, as the energy transition continues, over the coming decade.

DISCOVERY THROUGH THE AGES – A JOURNEY OF COAL RESOURCE DISCOVERY IN QUEENSLAND’S BOWEN BASIN FROM THE 1960S AND THE 2000S

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Exploration methods, technology and equipment may have changed greatly over the last few decades but still does not replace sound geological principles in making new coal resource discoveries. Starting with a case history of the early big discoveries in the Bowen Basin, Central Queensland, author and co presenter Mr Lex Hansen will provide an overview of the methods, techniques, equipment and successes of exploration during the early 1960s in the Bowen Basin.

Mr Hansen was a member of the team of three geologists working for Utah Development Company (purchased by BHP Ltd in the 1980s) that made the first big coking coal discoveries in the Bowen Basin extending from Blackwater in the south along the western side of the Basin to Goonyella in the north. The majority of these discoveries are still in production today, some 50 years later.

These will then be contrasted with a more recent case study involving greenfields discoveries at the Meteor Downs and Rockwood Projects as well as the world class brownfields coking coal discovery at Saraji East, located also in the Bowen Basin Central Queensland. This will provide a unique opportunity as to recent coal exploration methodology, technology and successes. Co-author and co-presenter Mr Darren Walker led the teams responsible for these discoveries.

The authors will then contrast and compare exploration from the ‘then’ and ‘now’ and discuss the importance of ‘grass roots’ geological field work, data analysis and principles in successful exploration regardless of the perceived exploration or resource maturity of a mineral province.

THE USE OF FWI IN COAL EXPLORATION

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3D reflection seismic is routinely used for a precise structural mapping of coal seams in Australia. Seismic images are used to analyse and predict underground hazards such as faults and folds, week strata, gassy zone, etc. Structural analysis of 3D seismic images is then utilised to help plan underground mining operations. While time seismic images are of a high quality; issues with depth conversion, fault through estimate, coal quality, presence of fractured and gassy zones, week strata, etc. are still to be fully resolved from seismic images. A step change in solving these issues could happen by incorporating Full Waveform Inversion (FWI) into seismic borehole and surface imaging flows. The seismic data quality in Bowen and Sydney basins is such that FWI could be applied over a wide frequency

band to produce high resolution P-wave and more importantly density images, particularly from VSP data that can be used for both depth imaging and directly for coal characterisation. We evaluate the potential of FWI for coal exploration in Australia by conducting comprehensive, log-derived simulation studies.

1040–1220
MONDAY 19 FEBRUARY 2018

1B WEST AUSTRALIAN BASINS SYMPOSIUM

HIGH IMPACT DATA CREATES HIGH IMPACT OPPORTUNITIES

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Modern developments in seismic imaging integrated with traditional geological methods have created exciting new exploration opportunities in areas traditionally considered frontier and low prospectivity or mature with very limited opportunities for significant new discoveries.

Extreme examples are presented, from opposite ends of the Australian continental plate and in vastly different tectonic regimes, illustrating the opportunities this new approach offers.

The horseshoe-shaped Banda Arc, north of Australia, has long been of interest to the exploration community because sedimentary rocks outcropping within islands of the region are essentially the same as those occurring on Australia's Northwest Shelf. Abundant oil and gas seeps on these islands, together with deep-sea seeps, attest to a working petroleum system in the area.

The Banda Arc (in reality an arc in the geometric not the geological sense), defined by two strongly curved, sub-parallel ridge systems with intervening troughs, is the site of collision between the northwards-moving Australo-Indian (continental/oceanic) Plate, the SW-moving oceanic Pacific Plate and the (relatively stable) southern promontory of the continental Asian Plate known as Sundaland. The present-day complex geology results from two opposing tectonic forces: northwards movement of the Australian Plate and sinistral shear on the Greater Sorong Fault System (the plate boundary between the Australian and Pacific plates).

Interpretation of new broadband seismic data and detailed geoscientific analysis has significantly improved understanding of geological development of the area.

Geological development has occurred in several distinct phases:

- Formation of a jagged passive margin (non-volcanic with hyperextension) and generation of oceanic crust in late Jurassic times.
- Cenozoic subduction of the Jurassic oceanic crust; slab rollback from about 15Ma.
- Arrival of continental crust into the subduction system around 10Ma, partial subduction until the system jammed, together with fold-and-thrust belt formation and the development of foredeeps (Timor, Tanimbar and Seram troughs) developed in front of the active fold-and-thrust belts.
- Continuing slab-push from the mid-ocean ridge (far) to the south resulting in widespread strike-slip faulting and wrench basin formation together with some obduction and isostatic rebound.

It is believed that the region is in the initial stages of orogenesis, comparable to the Eocene "soft collision" of Greater India with Asia which ultimately resulted in the formation of the Himalayas.

The Gippsland Basin in southeastern Australia is one of Australia's most prolific hydrocarbon systems, having historically generated approximately two thirds of the country's cumulative oil production and one third of its gas.

The basin has a long and proud history – 1964 Esso took over as operator of a joint venture with BHP and spectacular exploration successes followed.

The creaming curve for the basin is essentially flat since the mid-1970s, with no significant kick from either the application of 3D or deepwater success (as has occurred in many other basins of the world). While it could be argued that the curve flattened because the big discoveries have all be made, it could also be argued that imaging problems have masked significant opportunities.

Imaging issues in the basin have long been known: challenges include limited resolution at reservoir level, distortion from shallow complex overburden and poor imaging in the deep section.

Significant new exploration opportunities in the basin have been generated by a major reprocessing project involving application of several technologies. Technologies used include broadband processing, Full Waveform Inversion (FWI) and least squares Q PSDM (LSQPSDM).

Prospects with the potential to contain several trillion cubic feet of gas have been generated, highlighting the impact of enhanced imaging.

MAPPING NORTHERN AUSTRALIA'S PRESENT DAY STRESS FIELD: THE CANNING BASIN

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The Canning Basin is one of Australia's most prospective onshore petroleum basins, with proven petroleum systems and current production from conventional reservoirs. However, the majority of recent interest has been in unconventional hydrocarbons within the deeper basin depocentres, particularly the Ordovician Goldwyer Formation and the Lower Carboniferous Laurel Formation. Understanding the regional stress regime and geomechanical properties of reservoir units are some of the critical factors required to determine the basin's unconventional resource potential. Fluid flow pathways within the sub-surface units in unconventional plays are controlled by local and regional stresses and so understanding the present-day stress regime is integral to modern petroleum exploration and production. This study characterises the regional stress regime within the Canning Basin using existing well data and well tests to derive stress magnitudes and forms part of a greater effort from Geoscience Australia to understand the present-day stress field of northern Australia.

Generally, interpreted stress magnitudes in the Canning Basin indicate a strike-slip faulting stress regime. However, one-dimensional mechanical earth models constructed from dipole

sonic data indicate a consistent transition from strike-slip to normal faulting with depth, as well as limited local transitions to both normal and thrust faulting primarily due to significant local variations in vertical stress magnitude due to varying carbonate thickness and localised uplift, but also as a result of lithology. Borehole failure features interpreted from wellbore image logs yield an approximately NE–SW striking maximum horizontal stress azimuth with noticeable variations that are attributed to local stress perturbations.

REGIONAL JURASSIC SEDIMENT DEPOSITIONAL ARCHITECTURE, BROWSE BASIN: IMPLICATIONS FOR PETROLEUM SYSTEMS

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The Browse Basin hosts considerable gas and condensate resources, including the liquefied natural gas (LNG) developments at Ichthys/Prelude and Concerto fields. However, oil discoveries have been sub-economic and confined to the Caswell Sub-basin and Yampi Shelf. This multi-disciplinary study has mapped the hydrocarbon sources and areas of increased liquids prospectivity within the gas-prone basin.

Isochore maps and depositional models suggest multiple Jurassic and Cretaceous source rock units in compartmentalised pods, resulting in four geochemically distinct petroleum systems.

Organic-rich shales of the Upper Jurassic–Lower Cretaceous J40–K10 supersequences (Vulcan Formation) are believed to have sourced the gas in the encasing K10 sandstone reservoir (Brewster Member) in the Ichthys/Prelude and Burnside accumulations, and potentially other similar plays in the southern Caswell and Oobagooma sub-basins.

The gas sourced by the Lower–Middle Jurassic J10–J20 supersequences (Plover Formation) has assisted migration toward the basin margin, and is reservoired within the J10–J20 supersequences on Scott Reef Trend, the K10 supersequence in the Ichthys/Prelude field, and the shallow Lower Cretaceous K40 supersequence on the Yampi Shelf.

The Jurassic J10–J50 supersequences (Plover and lower Vulcan formations) in the Heywood Graben have generated fluids with a unique composition within the basin, and resemble a petroleum system in the Bonaparte Basin. These data integrated into a pseudo-3D petroleum systems model identified liquid-prone plays in the southern and northern Caswell Sub-basin, on the basin margins and in the Heywood Graben.

1040–1220
MONDAY 19 FEBRUARY 2018

1C EAST AUSTRALIAN BASINS SYMPOSIUM

TECTONICS AND GEODYNAMICS OF THE EASTERN TETHYS AND NORTHERN GONDWANA SINCE THE JURASSIC

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The tectonic and geodynamic evolution of the eastern Tethys since the Jurassic drove the opening of important hydrocarbon-bearing basins and emplacement of ore deposits on the northern margins of Gondwana and the southern margins of Eurasia. However, the geological record of these events is obscured by multiple subduction and collision events in equatorial regions where weathering and inaccessible geography has led to poor data coverage. We synthesise constraints from the geology to create end-member global plate motion models with regional refinements for Southeast Asia and the New Guinea margin using the open-source community GPlates software. The plate reconstructions are applied as boundary conditions in forward numerical models of mantle convection using CitcomS, with present-day mantle structure predictions validated using P- and S-wave seismic tomography. This approach enables us to use the deep Earth as an additional constraint to help refine the chronology of major rifting, subduction and collisional episodes. Our results suggest that the Philippine Arc and the Sepik terrane rifted from the Gondwana margin through slab rollback and back-arc opening processes. The Sepik back-arc basin was consumed from the Late Cretaceous, with accretion of the Sepik composite terrane occurring sometime in the Eocene (~52 to 35 Ma). The sinking of the Tethyan and Sepik slabs beneath the northward-moving Australian continent also modulated the regional topography that results from convection in the mantle. This evolving dynamic topography forms an important input for surface process models that provide insights into the depositional history of basins in New Guinea and Australia.

PREDICTING AND DETECTING CARBONATE CEMENTED ZONES WITHIN LATROBE GROUP RESERVOIRS OF THE GIPPSLAND BASIN

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A wireline log model predicts carbonate cemented zones within Late Cretaceous to Paleocene reservoir sandstones of the Latrobe Group, Gippsland Basin. Predictions match published evidence. These sandstones were once heavily cemented prior to development of secondary porosity that produced the world-class petroleum reservoirs we see today. Cemented zones that remain must act as obstructions to reservoir fluid migration. They may also react with the mild carbonic acid that will be introduced by CO_2 storage operations of the future. Model predictions show that cemented zones are sparse, spatially sporadic and fall well below seismic resolution at modern-day reservoir depths. Their significance and irregular spatial occurrence mean there is a need to map their distribution.

Synthetic seismograms generated for a number of Gippsland Basin wells predict high amplitude seismic reflectors away from major lithostratigraphic boundaries. Many occur where cemented zones are predicted. An investigation of the complex seismic trace demonstrates seismic sensitivity to these zones in the frequency range 100–125 Hz. An elevated moving average of instantaneous frequency correlates with some of them. Others are indicated by a change in the difference of normalised instantaneous amplitude between the original frequency-filtered complex trace and a frequency-filtered complex trace composed of sinusoids with the same magnitude and phase (arithmetic averages of the original complex trace). These subtle phase disturbances at high seismic frequencies are hypothesised to be caused by the presence of thin cemented zones. This idea is tested using instantaneous attributes of 3D seismic survey data available across the Gippsland Basin.

IMPACT OF SEQUENCE STRATIGRAPHIC FRAMEWORK ON STATIC AND DYNAMIC RESERVOIR MODELS: EXAMPLES FROM THE PRECIPICE-EVERGREEN SUCCESSION, SURAT BASIN, QUEENSLAND

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CO_2 storage in the subsurface is a key aspect of climate mitigation. The UQ is investigating whether the Precipice Sandstone and Evergreen Formation in the Surat Basin, Queensland, are an appropriate reservoir-seal pair for the long-term storage of greenhouse gases. However, the Precipice-Evergreen succession remains poorly constrained from a paleo-depositional and stratigraphic standpoint. Studies have mostly applied lithostratigraphy for local correlation, and the understanding of time-stratigraphic relationships across the basin needs development. This has greatly hindered the capacity to construct robust reservoir models and is an active area of research.

We utilised core, wireline logs, seismic data, as well as pressure data to compare the dynamic response to various CO_2-injection scenarios with contrasting stratigraphic architectures. A lithostratigraphic prediction of reservoir and seal intervals in the Myall Creek area, consisted of a layer-cake model of fluvial channel deposits. The model suggests that reservoirs are well connected with the gas plume primarily migrating in the lateral direction. In contrast, a sequence stratigraphic arrangement of facies resulted in greater reservoir compartmentalisation with some vertical fluid transmission across certain play segments. This is due to the fact that mudstone intervals baffle the CO_2 plume and compartmentalise the reservoir. The contrasting models show different geological realisations arising from the same dataset, interpreted in different ways.

Fluid flow is highly sensitive to the stratigraphic arrangement of reservoir intervals. Refining static and dynamic models using sequence stratigraphy results in a significant improvement in history matching. Modelers should carefully consider the implications of stratigraphic correlations during static model construction.

ORGANIC GEOCHEMISTRY AND PETROLEUM POTENTIAL OF OUTCROP AND CORE SAMPLES OF THE PERMIAN IN THE SOUTHERN SYDNEY BASIN

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Permian sediments occur throughout the southern Sydney Basin, exposed on the coastline south of Wollongong, and penetrated by various boreholes. This study uses outcrop samples and samples from three boreholes held by NSW Resources and Energy at the core library at Londonderry (Callala-1 from near Callala Bay, Elecom Clyde River DDH7 from near Nowra, and Elecom Clyde River DDH1 from near Wingello). Formations analysed include the Berry Siltstone, Nowra Sandstone, Wandrawandian Siltstone, the Snapper Point Formation, the Pebbley Beach Formation and the Yarrunga Coal Measures. The objectives are to determine the depositional environment, organic matter inputs, thermal maturity and petroleum generation potential of these formations, which were deposited when Australia was close to the South Pole. The rocks are thermally mature and were deposited in oxic to suboxic depositional environments. The Wandrawandian Siltstone contains biomarkers dominated by very high amounts of diahopanes and diasteranes, whereas these biomarkers are of lower relative abundance in the other formations. This is suggestive of a clay-rich sediment in an oxic, acid-catalysed depositional environment, with enhanced diagenetic alteration of the biomarkers, or alternatively an unusual organic input. The Pebbley Beach and Snapper Point formations are characterised by biomarker distributions dominated by terrestrially sourced terpanes (e.g. C_{24} tetracyclic terpane; C_{19} tricyclic terpane), corroborating their deltaic and shallow marine depositional environments, respectively. In contrast, the Wandrawandian Siltstone contains dominantly C_{21}, C_{23}, and C_{24} tricyclic terpanes. The Pebbley Beach Formation contains high amounts of C_{29} relative to C_{28} and C_{27} steranes, also consistent with a dominant terrigenous input.

1040–1220
MONDAY 19 FEBRUARY 2018

1D GEOLOGY CASE HISTORY

LITHOGEOCHEMISTRY OF PEGMATITES AT BROKEN HILL: AN EXPLORATION VECTOR TO MINERALISATION

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Pegmatites hosted in granulite and upper amphibolite facies metamorphic rocks are leucogranites, quartz-feldspar-mica or feldspar-rich pegmatites. These locally form large, sill-like, largely stratabound complexes within the lower part of the Willyama Supergroup. They are interpreted to have formed during anatexis and considered to be mostly *in situ*.

Those hosted in lower grade amphibolite and greenschist facies rocks are feldspar poor and quartz-muscovite rich, with tourmaline on their margins and as replacements of the surrounding protolith. They are volumetrically smaller than anatectic pegmatites and intrude and alter psammo-pelitic sequences in the upper parts of the Willyama Supergroup.

Data suggests a geochemical continuum from poorly evolved pegmatites hosted in high grade metamorphic rocks, lower in the stratigraphy, to more highly evolved types hosted in lower grade metamorphic rocks located in the upper parts of the stratigraphy.

Economic element content is similarly divided into two broad end-members. High grade metamorphic rocks host elevated Pb-Zn-Ag-Mn whereas lower grade metamorphic rocks host Sn-W mineralisation and elevated incompatible elements; Li-Nb-Cs-Rb-Tl-Ga-Ta.

We attribute elevated base metals in anatectic pegmatites to the enriched nature of those elements in the host protolith; the Broken Hill Group, the primary host to the Broken Hill Pb-Zn-Ag deposits and numerous BHT occurrences. In contrast, we attribute the Sn-W and incompatible element-enriched pegmatites to fractionation processes.

Exploration using systematic pegmatite geochemistry has the potential to enable vectoring toward buried BHT deposits in high grade metamorphic rocks. Similarly, the potential for Sn-W deposits and/or LCT (lithium-caesium-tantalum)-bearing pegmatite can be assessed in lower grade rock.

ORE AND GANGUE MINERALS OF THE HERA AU-PB-ZN-AG DEPOSIT, COBAR BASIN, NSW

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The Hera Au-base metal deposit, 5 km southeast of Nymagee, central New South Wales is on the eastern margin of the Palaeozoic Cobar Basin within the Lachlan Orogen. Discovered by Pasminco in 2001, the current total resource is 2.7Mt @ 4.1 g/t Au, 34 g/t Ag, 3.67% Pb and 4.86% Zn. The deposit occurs in a strongly altered and deformed sequence of shelf and turbiditic siltstones and fine-grained sandstones, members of the Nurri and Amphitheatre groups, with the majority of mineralisation occurring in the latter.

Ore minerals comprise pyrrhotite–sphalerite–galena ± chalcopyrite ± pyrite ± cubanite ± arsenopyrite ± tetrahedrite ± native Sb ± gudmundite, gold and scheelite occurring as massive and disseminated sulfides in vein/breccia zones. The main sulfides have composition as follows: pyrrhotite 60.5 wt% Fe and 38wt% S with traces of Co, Pb, Bi, Sb and Zn; sphalerite 56.4 wt% Zn, 8.9 wt% Fe, 33.5 wt% S, and traces of Pb and Bi; galena 86.4 wt% Pb and 13.4 wt% S with traces of Fe, Bi and Zn. Major gangue minerals consist of quartz, chlorite, biotite, and muscovite, with minor carbonate, actinolite/tremolite, Ca-rich garnet and rare titanite and fluorite. Relatively coarse-grained albite–quartz–chlorite rocks were recently discovered; however, their significance and emplacement mechanism is as yet unknown. The occurrence of skarn-like assemblages and albite-quartz-chlorite rocks suggests that at least some of the lodes at Hera differ significantly from typical sediment-hosted 'Cobar-style' deposit as previously suggested. This is also supported by field observations, petrographic analysis and XRD and shows that the host rocks have been metamorphosed to upper greenschist to lower amphibolite facies.

1040–1220
MONDAY 19 FEBRUARY 2018

1E IP FROM EM SURVEYS

MODELLING IP EFFECTS IN AIRBORNE TIME DOMAIN ELECTROMAGNETICS

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The presence of chargeable material can significantly impact the data in electromagnetic (EM) surveys. This affected data has traditionally been treated as noise that must be removed prior to interpretation or inversion. The ability to extract induced polarisation (IP) information from an airborne platform would be a valuable tool in the mineral exploration industry and the

pursuit of this ability has recently led to significant interest in the interpretation of IP effects in airborne data. A variety of interpretation methodologies have been proposed to aid in the identification and extraction of information from time domain EM data containing IP effects.

Any interpretation scheme needs to be thoroughly tested on realistic synthetic examples so that the strengths and weaknesses of the method are well understood. In this work, we present a methodology for accurately and efficiently simulating the response of a time domain EM experiment by modelling the convolution that occurs in Ohm's Law in the presence of a frequency dependent conductivity. This method is free of any assumptions about the dimensionality or frequency dependence of the chargeable material and can be used to simulate the response of any time domain system. The importance of considering the problem in three dimensions is demonstrated, and the problems that could arise from working with a reduced dimensionality are demonstrated.

A THOROUGH SYNTHETIC STUDY ON IP EFFECTS IN AEM DATA FROM DIFFERENT SYSTEMS

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IP effects in AEM data are subject of current research around the world, due to the recent recognition of their significance for exploration and general (hydro)geological mapping. There is however a need to study more accurately the boundaries of the effect and of its relevance. In this paper we present, based on synthetic modelling, a systematic, extended analysis of AIP effect from different AEM (TEM) systems in different pseudo geologies. Its goal is to provide a clear overview of possible AIP effects in the data space, without imposing simplistic assumptions (e.g. fixing some parameters to arbitrary values or limited boundaries). We produce 1D FWD responses with dispersive resistivity for hundreds of thousands of combinations of Cole–Cole model parameters and AEM system transfer functions. The results are analysed using various metrics (e.g. sum of negative voltages, exponential fitting) that capture different AIP signatures in the transients. Experiments include half spaces, 2 and 3 layer models, combined with different waveforms, Rx types (dB/dt and B), Tx–Rx geometries, flying heights, transients' binning, base frequencies. The results, presented as 4D hyperspaces, each with 10^4 transients obtained from the combinations of 4×10 different Cole-Cole parameters, allow a clear assessment of the AIP effects over a wide range of geophysical situations. Some of the main observations are: AIP effects are increased by the presence of a resistive bedrock, using slow turn-off of the waveform and better observed recording the B field instead of its derivative and in any case adopting low base frequencies.

AIRBORNE EM AND IP BELOW 10 HZ

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Most good time domain AEM systems use a base frequency at or above 25 Hz. This keynote describes progress towards the development of viable extremely low base frequency 3 Hz base frequency airborne system. Suspended vector magnetic field sensors, whether B or dB/dt, rotate in the earth's magnetic field and pick up large unwanted signals, often called 'motion noise'. It is this low-frequency noise that has in the past constrained commercial AEM systems to operate at base frequencies of 25 Hz or more. There are four conceptual mechanisms to improve signal/noise ratios in an AEM system: increase transmitter dipole moment by several orders of magnitude, engineer more stable suspension systems, make rotation measurements and correct the measured B field response, or devise new waveforms and processing strategies that better separate and reduce noise levels.

Power supplies and weight constraints are close to their limit in appropriate aircraft, implying that increasing dipole moments by an order of magnitude or two is impossible using current technology. Most research effort by contractors has addressed suspension systems, with limited successes reported to date. The BIPTEM (B field IP; Time domain EM) system currently under development in Australia has used a combination of rotation rate sensing, waveform optimisation and an improved suspension to collect useful inductive magnetometer B and dB/dt field data at extremely low base frequencies, and been successfully tested over known IP targets.

1040–1220
MONDAY 19 FEBRUARY 2018

1F INVERSION MODELLING METHODS

COOPERATIVE INVERSION: A REVIEW

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Cooperative inversion is increasingly recognised as having the potential to significantly improve subsurface imaging for a range of parameters. However, there is no doubt success or failure is also highly dependent on a good knowledge of the underlying site specific geological and petrophysical relationships. Combinations of structural or textural seismic attributes can be used with geostatistical clustering methods to provide a framework able to carry inversion of lower resolution EM or potential field data to much higher resolution. Cross gradient type methods use direction of change of petrophysical parameters as a lever to push inversion towards an improved outcome. But again, the outcome is highly dependent on the presumption that the direction of change of petrophysical parameters like velocity and electrical conductivity are somehow linked. We need some way to build relationships between petrophysical parameters which could come in the form of new multiscale, multiparameter measurements made during drilling. We will: (1) examine theoretical possibilities; (2) give examples

of practical successes and failures; and (3) consider the future of cooperative inversion.

APPLICATION OF GEOLOGICALLY CONDITIONED PETROPHYSICAL CONSTRAINTS IN JOINT INVERSION: A CASE STUDY

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Quantitative integration of geology, petrophysics and geophysics in a single inversion scheme is a complex, yet theoretically powerful method to solve challenges faced in exploration scenarios. In this work, we present a case study illustrating the improvements in subsurface imaging and uncertainty reduction brought by the integration of probabilistic geological modelling and petrophysical constraints in three-dimensional geophysical joint inversion. The area investigated is located in the Yerrida Basin (Yilgarn Craton, Western Australia). The main difficulty encountered by previous studies was to characterise the thickness of the overburden, thought to be in contact with a potentially mineral-rich basement. Using gravity and magnetic data, results show that the use of constraints derived from the statistics of petrophysical measurements in inversion permits to retrieve sharp contrasts and to delineate geological units directly. The use of probabilistic geological modelling to condition the petrophysical constraints allows to (1) refine the inverted model by enforcing geological consistency, and (2) reduces the impact of inversion's inherent non-uniqueness. Finally, statistical and structural analysis of the results suggest that areas previously considered too uncertain may show good prospectivity, highlighting areas for future exploration targeting.

CONSTRAINING AN INVERSION TO FOLLOW CURVING TRENDS IN AN IMAGE

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This paper addresses the question of how to include structural information, for example from a magnetic image, into an airborne electromagnetic (AEM) inversion.

The kind of information we are interested in is the trend directions seen in the magnetic image, such as strike directions of dipping bodies, or the shape of palaeochannels.

A commonly-used technique for including prior information is to use a model covariance matrix, describing the spatial covariance between different model points. However, these covariances are usually constructed from a stationary covariance function which is dependent on the vector distance between two points, but is the same for the entire model. However, if a palaeochannel is visible in the magnetics, then we know that the AEM model is more likely to be similar along the channel than away from the channel. We therefore wish to construct a covariance matrix that can take curved and branching structure into account.

We construct an inhomogeneous covariance matrix from an image by breaking the image up into multiple windows, and then computing an elliptical distance metric in each window, such that distances in the direction of the features in that window are shorter than distances across those features. This collection of distance metrics then allows us to compute, between any two points in the image, a shortest path that curves to follow the directions of trends in the image. Using this curved-path distance allows us to generate a covariance matrix that encourages the inverted model to follow the trends in the image.

EXPLORING INVERSION SOLUTION SPACE: A CASE STUDY OVER A CU-AG DEPOSIT IN THE KALAHARI COPPER BELT

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Interpretation of geophysical data remains an extremely challenging task in spite of improvements in instrumentation, acquisition, inversion and visualisation. The root cause of this difficulty is well known: different earth manifestations can give rise to the same geophysical response. Given this root cause it is inescapable that any workflow based solely on inverting geophysical data to produce a single earth model is incomplete at best, and at worst, misleading. To reduce this incompleteness we recommend extending the usual process of inversion yielding a single model to include an exploration of the solution space of models all of which give rise to the same geophysical observations. As an illustration we present an inversion case study revolving around a 3D DCIP data set obtained over the recently discovered T3 Dome Cu-Ag deposit in the Kalahari Copper Belt (KCB) in Botswana. We explore the inversion solution space using a suite of models produced by introducing various constraints. In our study standard unconstrained inversion yields a deep smooth chargeability model however drilling results appear to suggest a different chargeability distribution. The exploration question becomes: how robust is the deep chargeable target, is it indicative of new sulfides or is it a manifestation of model equivalence? We demonstrate how to attack such problems, which leads us to suggest that by default all geophysical inversion algorithms should produce several equivalent models to help move the exploration community beyond the idea that a single inversion result is 'the model'.

1040–1220
MONDAY 19 FEBRUARY 2018

1G REGIONAL TECTONIC

PALAEOMAGNETIC TEST OF OROCLINAL ROTATION IN THE DUNDAS TROUGH, TASMANIA

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Palaeozoic units of the Dundas Trough in western and northern Tasmania, which include the richly endowed Mount Read

Volcanics, form an arcuate trend in outcrop and aeromagnetic images, wrapping around the Pre-Cambrian Tyennan region. Previous interpretations attributed the arcuate shape to sedimentation in pre-existing curved rift and graben systems, without rotation. New studies have reinterpreted the Trough as the result of oroclinal rotation of a former linear orogen. Palaeomagnetic samples were collected from selected early Palaeozoic sedimentary sequences at 22 localities around the Dundas Trough and correlative formations in the Adamsfield–Jubilee region. Low-temperature and thermal demagnetisation was conducted on most samples with selected units also demagnetised with the alternating field technique. From the 22 localities sampled, 11 produced clear demagnetisation results. Principal component analysis was used to determine characteristic remanent magnetisation (ChRM) directions.

Oroclinal rotation was tested by plotting ChRM declinations against regional strike (the 'palaeomagnetic orocline test'). Declination correlates with strike, verifying the orocline hypothesis. Average declinations in the north-east limb of the trough (Dm 97.2°, Im 36.2°) suggest a clockwise rotation ~90°. A paleomagnetic pole determined from the western limb of the trough falls on the early Palaeozoic Gondwana apparent polar wander path, confirming that this limb was fixed to cratonic Australia.

These results both confirm the oroclinal curvature of the Dundas Trough, implying its continuation under Jurassic cover in eastern Tasmania, and more broadly support the hypothesis that oroclines played a fundamental role in crustal accretion in eastern Australia.

MAPPING METASOMATISED MANTLE BY INTEGRATING MAGNETOTELLURIC, PASSIVE SEISMIC AND GEOCHEMICAL DATASETS – SE AUSTRALIA

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There is growing evidence that the distribution of giant magmatic and hydrothermal ore deposits are linked to the presence or absence of metasomatised lithospheric mantle. It follows that mapping the distribution of this mantle should be an important component of exploration programs for world class deposits, yet to date there has not been a robust means of spatially constraining the distribution of metasomatised mantle. Classically, metasomatism has been identified through petrological and geochemical analysis of mantle xenoliths and mantle derived melts which provide information on the vertical distribution of metasomatism beneath magmatic centres. Here, we show this classical information integrated with constraints on lithospheric thickness and conductivity, derived from passive seismic and magentotelluric imaging of the lithosphere provide an effective means of mapping both the lateral and vertical distribution of mantle metasomatism. As a case study we show the integration of the aforementioned datasets over south-eastern Australia where the Australian Lithospheric Architecture Magnetotelluric Project (AusLAMP) was started.

GEOSCIENCE AUSTRALIA'S CONTRIBUTION TO AUSARRAY – PASSIVE SEISMIC IMAGING OF AUSTRALIA

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Geoscience Australia (GA), as a part of the exploring for the future program, is aiming to create a high resolution three-dimensional (3D) seismic model of Australia to infer physical properties of the lithosphere from depths of few meters to hundreds of kilometres. This work is based on new data collected from national seismological network and a new movable seismic array complemented by legacy seismological data obtained by universities. GA has deployed a movable array of 135 broadband seismic stations for one year between Mount Isa and Tennant Creek arranged in a grid pattern with interstation distance of approximately 55 km in order to attain horizontal resolution of at least 20 km. This dense network is reinforced by 15 semi-permanent higher sensitivity broadband seismic stations located predominantly in the Northern Territory and Western Australia in order to increase imaging resolution within the array and within areas where national seismological network has gaps. Multiple seismological methods are being combined together to obtain robust constraints on 3D lithospheric architecture. For the first time, particular attention is focused on shallow structures located at depths of less than 1 km.

COORDINATING AND DELIVERING A 1.8 MILLION LINE KILOMETRE MAGNETIC AND RADIOMETRIC SURVEY – A STATE GOVERNMENT PERSPECTIVE

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In January 2017 the largest airborne magnetic, radiometric and elevation survey in South Australia's history began in the Gawler Craton. The aim of the South Australian Government is to use the survey as an opportunity to achieve best practice in relation to the coordination, landholder liaison, reporting and quality control of the survey, in tandem with collaborative partners at Geoscience Australia. Some of the outcomes include a landholder and stakeholder information website, subscriber email updates, close liaison with field capture teams, timely delivery of survey data and results, and a proactive approach in ensuring the data captured is of consistent, high quality across the entire survey region. The survey is been performed in three stages and each stage provides an opportunity to assess approaches and fine tune requirements. It is expected that the end result will set a benchmark for other jurisdictions performing similar work.

1040–1220
MONDAY 19 FEBRUARY 2018

1H GEOTECHNICAL AND ENVIRONMENTAL

TRACKING THE DIPROTODON – MICROTREMOR PASSIVE SEISMIC PROFILING AS A TOOL FOR LOCATION OF MEGAFAUNA BONE BEDS

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Bone beds containing Pleistocene megafauna remains dated to between 35 ka and 60 ka occur near Lancefield (Vic). The bones lie within clays above gravels and extensive Quaternary basalt flows. Evidence that the bones have been subject to alluvial transportation suggests that profiling the basalt basement for paleo-channels will assist with locating further bone beds. Passive seismic (microtremor) methods, as developed variously for earthquake hazard studies and regolith studies, have been applied to this problem, using both H/V methods and two-station SPAC (spatially averaged coherency) methods. Clay layers have shear-wave velocities (Vs) in the range 100–150 m/s and thicknesses 3.5 to 4.5 m. Microtremor data in the frequency band 10–50 Hz provides excellent resolution of the Vs and thickness of the clay layers, allowing the bedrock profile to be established to an accuracy of 0.5 m or better.

AN INTEGRATED ANALYSIS OF GEOPHYSICAL DATA FOR LANDSLIDE RISK ASSESSMENT

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In May 2014, a severe storm caused substantial damage in the Balkan area by floods and landslides. As a contribution of geophysicists and geotechnical engineers to the effort of prevention of further damage, a Geoscientists *without* Borders (G*w*B) project was organised by Association of Geoscientists and Environmentalists of Serbia to assess the potential of further occurrence of landslide in the region. This project was supported by SEG and many other organisations, governments and individuals of many countries. Local and international experts conducted field data acquisition with students from four countries. The project benefited the students to get practical experience in geophysical fieldwork, local governments received information of landslide risk in their area and the residents of the area were made aware of landslide potential of around their home land.

Geophysical surveys with seismic and electric methods were carried out in three phases, June and September 2015 and June 2016, in six locations in Serbia and Bosnia and Herzegovina. About 7000 m of seismic data were acquired at the sites where landslide potential is considered high. A lesser number of electrical surveys were conducted at the same locations. This paper presents some of the results of the geophysical surveys at some of the project areas comparing seismic reflection, MASW and electric resistivity methods, and subsequent assessment of risk of landslide. This information is being used by the engineers of local government in their plan for mitigation of disasters.

THE APPLICATION OF VSP IN THE PILBARA

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The construction of geotechnical models in typical Pilbara iron ore environments is vital to enable an optimised mine design while maintaining pit wall integrity. These models require the measurement of geomechanical properties, such as the modulus of elasticity, in-situ stress, unconfined compressive strength, and pressure and shear wave seismic velocities, from diamond core samples. Ideally these velocities would be measured in Reverse Circulation (RC) boreholes as their spatial density is far higher than diamond drilled holes. Unfortunately, despite its value, such data is seldom collected as a large proportion of the holes are above the water table, limiting the use of sonic-logging tools. Even if measurements are possible, damage to the borehole caused by drilling biases the resulting velocity measurements.

This paper details the results of a trial using the vertical seismic profile method to directly measure *in situ* seismic velocities in RC boreholes. The method was successful in determining the velocities of the formations; which turned out to be lower than those measured directly from core samples. This has implications for the pit designs including pit walls angles and locations, which can affect the cost of mining. The data in several boreholes was of sufficient quality for more advanced processing methods, important for geological mapping and the processing and interpretation of surface seismic data.

The success of this first trial has implications for future iron-ore developments in the Pilbara. The widespread acquisition of accurate seismic velocity data will enable the creation of more accurate geotechnical models and improved development decisions.

APPLICATION OF THE PASSIVE SEISMIC HORIZONTAL OVER VERTICAL SPECTRAL RATIO (HVSR) TECHNIQUE FOR EMBANKMENT INTEGRITY MONITORING

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Embankments are common features in mine sites necessary for tailings storage, surface water management or general infrastructure such as dewatering ponds. Differing construction methodologies, from loosely placed waste material to engineered and individually compacted lifts, will achieve varying density, strength and permeability. Conventional construction quality assurance is however not always possible without causing significant interruptions to the construction program and compromising the embankment integrity. Estimating levees' bulk shear wave velocities via passive seismic HVSR surveying as a proxy for stiffness is a practical, continuous and non-invasive

method that can be carried out with limited construction interruption. This also provides a continuous dataset throughout the embankment as opposed to discrete observations using conventional geotechnical methods.

Field data acquired over the length of several embankment types demonstrate the very good correlation between estimated bulk shear wave velocities and the levees' degree of compaction. As a result, alternative construction methodologies can be quantitatively benchmarked against a bulk density spectrum with fully engineered embankments and loose waste dumps as end-members. Collection of repeated measurements over time also discriminated stable embankments from settling ones, and constitutes a cost-effective way to identify possible zones of weakness before hazardous failure.

1345–1500
MONDAY 19 FEBRUARY 2018

2A COAL

SEISMIC DIFFRACTION IMAGING FOR IMPROVED COAL STRUCTURAL DETECTION IN COMPLEX GEOLOGICAL ENVIRONMENTS

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Faults and dykes are the most significant geological structures that have the potential to disrupt underground coal mining operations. Seismic reflection surveying, especially 3D seismic, is the primary technique for structural delineation ahead of any longwall development in the Australian coal mining industry. It is generally accepted that seismic reflection surveys have the ability to locate faults with throws greater than 5–10 m for 2D and 2–5 m throws for 3D seismic data, but detection of faults with smaller throws, shears and dykes with widths of a few metres remains a challenge to seismic methods. Near the seismic detection limit the risk of interpreting non-existent structures also increases.

In this paper, we describe a moving average error filter (MAEF) applied in the neighbouring traces to extract diffractions from post-stack reflection seismic data. The filter estimates the reflections with the average values of the neighbouring traces along the reflection direction or dip, which can be computed by the gradients of seismic data. The difference (or error) between the original data and the estimated reflections, yields the diffractions. By identifying diffractions, small faults and other minor features that are difficult to detect using conventional seismic reflection processing can be detected. Numerical and real data examples are used to illustrate the effectiveness of the proposed method in small coal seam structure detection by extracting diffractions from reflection seismic data in a relatively complex geological environment.

INTEGRATION OF DOWNHOLE GEOPHYSICAL AND LITHOLOGICAL DATA FROM COAL EXPLORATION DRILLHOLES

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The primary variable of interest in a coal resource study is the volume of coal as estimated from the coal thicknesses in each drillhole. It is therefore essential to accurately determine, down to the centimetre level, the thickness of each seam. To attain this accuracy, every drillhole is geophysically logged as the geophysical logs are a much more accurate indicator of seam boundary depths than the geologist's log. Currently, coal geologists spend large amounts of their time integrating their logs with depth information from the geophysical logs. They do this by displaying the two logs next to each other and then manually changing the depths in their logs. Most of this process is relatively routine and thus rather tedious and boring but like many seemingly simple cognitive tasks, not easily transformed into a computer algorithm. The manual methods also suffer from being subjective.

Previous methods to automate this process have used multivariate statistical techniques to assign lithologies down the hole based on the geophysical values at each reading depth. However, despite these methods having been developed and publicised for over thirty years they still have not been widely adopted as they still do not integrate the two sets of data. Geologists still must manually integrate two separate logs.

This current study has successfully managed to develop algorithms to automatically determine both coal/non-coal and clayey/non-clayey boundaries based on the gradients and inflection points of the geophysical logs and then integrate this information with the geologist's log.

QUANTIFYING GAS CONTENT IN COALS USING BOREHOLE MAGNETIC RESONANCE

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Evaluating gas content in coals has significant commercial and operational importance. In coal seam gas exploration and development, gas contained in coal seams is the resource of interest. In coal mining, quantifying gas content and evaluating the effectiveness of degassing is essential to safe mining operations.

Traditional approaches to saturation evaluation in conventional oil and gas reservoirs rely on relationships between resistivity and water saturation. These relationships are challenging to apply in coals due to complexities in their pore systems and gas trapping mechanisms. Therefore, geophysical log-based methods are not commonly employed for saturation evaluation, and core canister desorption measurements are the standard approach for gas content evaluation. Desorption measurements present their own challenge due to the unknown and variable volume of gas lost during core recovery, so an *in situ* measurement of gas content is desirable.

Advanced magnetic resonance measurements are one method of resistivity-independent saturation evaluation that have been employed in the oil and gas industry for the past approximately fifteen years. However, previous approaches to these types of measurements have focused on the evaluation of conventional reservoirs and hence free gas and oil volumes, and have lacked sensitivity to adsorbed gas, which has a different magnetic resonance response. A novel magnetic resonance acquisition scheme has been developed that provides sensitivity to both adsorbed and free gas, as well as water, allowing for the complete evaluation of fluid content in coal seams. This measurement has been employed in evaluating coal gas content for mining optimisation with encouraging results.

1345–1500 MONDAY 19 FEBRUARY 2018

2B WEST AUSTRALIAN BASINS SYMPOSIUM

EVOLUTION OF 'TRES HOMBRES' - A LARGE MID-CRUSTAL DOME STRUCTURE WITHIN THE NORTHERN BEAGLE SUB-BASIN WESTERN AUSTRALIA: AN INTEGRATED GEOPHYSICAL INVESTIGATION

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The Tres Hombres structure is a large enigmatic, mid-crustal structural feature that that underlies the Permian – Late Jurassic mega-sequences of the Northern Beagle Sub-basin, Western Australia. Originally identified on regional 2D seismic lines, the Tres Hombres structure has now, for the first time, been fully imaged by high quality, deep record, modern 3D seismic data. The area is also covered by modern gravity and magnetic datasets which were acquired together with the seismic survey. Seismic mapping reveals a dome-like structure with a diameter of more than 30 km, and with vertical relief of over 5 km. This paper integrates seismic and potential fields datasets to explore the origins of this intriguing structure.

Potential mechanisms considered for the emplacement of this feature include; basement cored compression, reactivated extensional basement faulting, remnant Palaeozoic topographic relief, salt-related diapirism, or plutonic/igneous intrusive activity. The actual mechanism responsible for the evolution of the Tres Hombres feature has important implications for adjacent and overlying petroleum systems within the Beagle Sub-basin – in particular trap timing, and thermal history.

Detailed mapping of the new 3D seismic dataset enables structural and stratigraphic restorations to be generated, which provide valuable insights into the timing of the Tres Hombres feature. Variations in the thicknesses of overlying sequences show the influence that this structure had on the stratigraphic evolution of the basin. Gravity and magnetic datasets have also been integrated into this study. These datasets provide valuable controls on potential lithologies within the core of Tres Hombres, which in turn have important implications as to the origin of this structure, and relationships to the tectonic evolution of the Beagle Basin.

CONTROLS ON MESOZOIC RIFT-RELATED UPLIFT SYN-EXTENTIONAL SEDIMENTATION IN THE EXMOUTH PLATEAU

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The Exmouth Plateau, part of the Northern Carnarvon Basin, has experienced a multi-phase extensional history, which is associated with regional scale uplift, as well the uplift and erosion of individual footwall blocks. Detailed interpretation of 3D seismic surveys over the area shows that fault activity began in in the latest Triassic, mainly on NE–SW trending faults. This created barriers to sediment transport, resulting in sediment starved half graben and onlap of sediments onto upthrown fault blocks. Further erosion of pre-rift Triassic sediment occurred during the Jurassic, though uplift had ceased and only the larger faults remained active. The Late Jurassic brought about a new phase of uplift in the south, possibly associated with the reactivation of north-south trending faults. By the earliest Cretaceous all major faults were once again active. A significant change in sediment supply in the Early Cretaceous associated with progradation of the Barrow Delta resulted in the infilling of previously starved half-grabens. Fault activity had slowed by the end of the Cretaceous, with limited activity confined to major faults.

The high quality of the 3D seismic data allows a detailed examination of the way in which rift related fault activity affects sediment distribution. In addition to creating fault block traps in pre-rift Triassic sediments, understanding syn-extesnional sediment patterns and fault reactivation has implications for syn-rift plays and seal integrity.

SHELF-MARGIN ARCHITECTURE AND SHORELINE PROCESSES AT THE SHELF-EDGE: CONTROLS ON SEDIMENT PARTITIONING AND PREDICTION OF DEEP-WATER DEPOSITION STYLE

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The Lower Barrow Group (LBG; Latest Tithonian – Early Valanginian) is a shelf-margin that prograded during a late phase of rifting under various subsidence regimes and supply-dominated conditions. A 3D semi-automatic, full-volume seismic interpretation method allow identifying high-order clinothems presenting an estimated cyclicity of ~40 000 years, in which a quantitative analysis of the shelf-margin architecture and shorelines processes was conducted. Overall, three and four main types of hydrodynamic regimes and deep-water systems were identified, respectively.

Falling to flat shelf-edge trajectories are associated with sediment bypass, whereas rising shelf-edge trajectories are linked with increasing sediment storage on the shelf. While fluvial to wave processes can be dominant in all A/S conditions, results show that fluvial-dominated coastlines are associated with steep high-angle slope clinoforms and short to longer run-out turbidites. Conversely, wave-dominated coastlines are linked to low-angle slope clinoforms and poor turbidite system development (occasional sheet sand and MTDs).

The short and longer run-out turbidite systems present a tripartite architecture (canyon/slope valley; channel; lobes), which mostly appear as short-lived, vertically/laterally stacked elements fed by multiple small rivers forming linear ramp systems. Due to the shallow configuration of the margin (<500 m), the presence of short slopes and overall high sand-to-mud ratio, the turbidite systems are smaller scale (<50 km) and probably shorter lived than most modern turbidite systems (100–1000 km).

This study sheds new lights on the significant role of shelf-margin architecture (slope gradient, hydrodynamic regime) in predicting the deep-water sediment delivery behavior (sediment partitioning, type of deep-water system).

1345–1500
MONDAY 19 FEBRUARY 2018

2C EAST AUSTRALIAN BASINS SYMPOSIUM

TARGETING CORE SAMPLING WITH MACHINE LEARNING: CASE STUDY FROM THE SPRINGBOK FORMATION, SURAT BASIN

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We show how clustering algorithms and mixing models can ensure that the core intervals that are pertinent to specific objectives of a sampling campaign are actually sampled and how the amount of samples can be reduced.

Why target sampling?

The clay phases in the Jurassic Springbok Formation generally do not exhibit a prominent gamma ray signature and are therefore poorly defined in well logs. Similar, hydrological properties of the Springbok Formation are not well defined through well logs. This introduces uncertainty to groundwater models of the Springbok Formation. Hence, a better understanding of the clay distribution is thought to be a key to improve the definition of the hydrological properties of the Springbok Formation.

How we targeted the sampling.

We applied our approach to five study wells from the Surat Basin in Queensland. We tailored the application of the cluster analysis and mixing models to our working hypothesis that the variability of hydrogeological properties of the Springbok Formation is controlled by the presence and type of clays, rather than compaction. This informed our choice of logs to include in the clustering (nuclear logs) and of logs to be used for control proposes (resistivity logs).

Results

We show that identification of five clusters was the most useful number towards our sampling objectives. This allowed for example to exclude coal and siderite layers from sampling for clay analysis and to focus on the differentiation of the clastic sediments in the formation. Further, we show that certain clusters correlate with resistivity log signatures.

THE INFLUENCE OF REVERSE-REACTIVATED NORMAL FAULTS ON POROSITY AND PERMEABILITY IN SANDSTONES: A CASE STUDY AT CASTLE COVE, OTWAY BASIN

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An understanding of fault zone structure and transmissibility can have significant implications for reservoir appraisal and development within petroleum systems. Previous studies have demonstrated that porosity and permeability is significantly reduced adjacent to fault zones due to pore collapse, grain crushing, and cement precipitation during deformation. We present results from a detailed mineralogical and geomechanical investigation of the Castle Cove Fault within the Otway Basin at Castle Cove, southeast Australia. Castle Cove provides excellent exposures of the Lower Cretaceous Eumeralla Formation, which is a fine-grained volcanogenic sandstone with moderate to highly porosity (up to 27%), but with generally low permeability (mostly <1 mD). The Castle Cove Fault originated as a normal fault during the late Cretaceous and was reverse-reactivated during NW–SE mid-Eocene to Recent compression. Core plugs were sampled at distances between 0.5 to 225 m from the fault and were orientated with respect to the fault plane. We show that closer to the fault (within 75 m), porosity increases by nearly 10% (i.e. from approximately 17% to 24%) and permeability increases by two orders of magnitude (from 0.02 mD to 3.74 mD). Microstructural investigations from thin sections show an increase in microfracture intensities closer to the fault. This study highlights the importance of detailed mineralogical and geomechanical analyses when attempting to understand fault seal generation and reservoir properties in high porosity and low permeability sandstones.

HIGH FREQUENCY REFRACTION/ REFLECTION FULL-WAVEFORM INVERSION CASE STUDY FROM NORTH WEST SHELF OFFSHORE AUSTRALIA

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The robustness of diving wave Full-Waveform Inversion (FWI) has been proven in industry, but the effectiveness is limited by its penetration depth. To target deeper reservoirs, the application of FWI using reflection energy is necessary. This paper presents a real data 25 Hz VTI FWI case study from North-West Shelf (NWS) Australia utilising the full wave-field. Starting from a high-quality reflection tomography VTI model, a top-down approach has been adopted. Diving wave FWI updates the

shallow, then reflection FWI is introduced to further update the deeper section. The updated FWI model demonstrates significant uplifts in increasing resolution and conformance with underlying geology. Two promising aspects can be observed: (1) the fairly solid uplifts in mitigating the imaging challenges: FWI reduces wave-field distortions, leads to overall improved focusing, gather flatness, continuity, and better positioning in depth; and (2) uncovers geological features beyond imaging: high-resolution FWI delineates small shallow anomalies and velocity boundaries across faults, and reveals the strong acoustic impedance contrasts at reservoir level. It demonstrates FWI can aid both in reducing the velocity uncertainty as well as understanding underlying geological formation.

1345–1500
MONDAY 19 FEBRUARY 2018

2D GEOLOGY CASE HISTORY

PATHFINDER EXPLORATION TECHNIQUES TO TARGET PORPHYRY AND EPITHERMAL STYLE ALTERATION SYSTEMS IN THE TEMORA COPPER-GOLD BELT

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The Temora project lies in the Lachlan Fold Belt between West Wyalong and Temora in the central-west of NSW. A number of mineralised systems are defined within the Late Ordovician Gidginbung Volcanic Complex including the mined Gidgingbung high sulphidation gold mine and a number of mineralised porphyry prospects.

Mineralisation is related to narrow intrusive dykes within a coeval volcanic pile of volcaniclastics, sediments and lavas. Quartz-magnetite-feldspar-pyrite-chalcopyrite veins are associated with a chlorite-magnetite-carbonate alteration. A later quartz-sericite-pyrite alteration postdates the mineralisation (B. Mowat and S. Smith, 2006).

Sandfire Resources targeted the district considered to retain excellent potential for large economic discoveries, purchased 100% of the project in 2015, and commenced a detailed review prior to field exploration drilling starting in late 2016. Availability of historical drill pulps, chip samples and drill core facilitated re-analysis of numerous holes with multi-element geochemistry and by Short Wave Infrared (SWIR) analysis using an Analytical Spectral Device (ASD). The white mica compositions, eg illite, sericite and muscovite and their spectral wavelengths, provided a zonation of alteration minerals highlighting potential vectors towards higher temperature fluids.

Priority targets were highlighted across the belt, including targets at depth associated with the Gidginbung high sulphidation epithermal gold system and the northern and eastern margins of the Rain Hill monzodiorite intrusive centre (Internal reports, Kitto 2016).

Drilling during the 2016–2017 field season in the Rain Hill has encountered a new prospect with porphyry style mineralisation at the Donnington prospect, (Sandfire QR March 2017).

1345–1500
MONDAY 19 FEBRUARY 2018

2E EM & DEEP RADAR

2.5D VS 1D AEM FORWARD AND INVERSION METHODS AT A SURVEY SCALE: A CASE STUDY

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The McArthur basin/EMU fault study has a classic 2D fault feature and a buried conductor with an off-end effect with other 2D/3D effects away from the EMU fault. The collected AEM data has demonstrable AIP effects. This has stimulated an investigation of a simple 2D geology cross-section of a dipping fault with a strong conductor on one side of the fault.

A forward model of the predicted response near the EMU fault represents a synthetic observed signal from the cross-section in agreement with the AEM data. Our modelling shows that the 1D inversion gives results which do not reproduce the survey data whereas 2.5D performs well reconciling the inverted section with the observed EM response. Away from the 2D geology region and other 2D/3D EM effects, 1D does perform well as expected. Therefore 2.5D gets it right in significantly more situations by honouring the information in the observed data raising questions about the use of 1D.

Emerging AEM systems can provide estimates of economic rock unit thicknesses, dips, faults and anticline/syncline definition at an accuracy that mitigates the need for pattern drilling. The use of 2.5D allows marker beds of more conductive material to stand out at a depth of 500 m or more on sections created beneath individual flight lines. Routine treatment of all survey data is now possible without supercomputing capability.

CSIRO has also recently undertaken comparative studies of the available AEM 1D, 2.5D and 3D inversion codes. Their work raises some stark reminders of what is different in the methodologies and how the progression to higher-order geophysics methods requires not just careful test work but also effective education of the user community.

We explain the fundamental differences between 1D and 2.5D and point out issues with the 1D forward modelling and inversion technology. Importantly, Maxwell's equations are used to constrain 2.5D whilst empirical methods are commonly used in 1D.

This leads to the situation where a near zero average misfit using stitched 1D models can be achieved with families of 1D inversions, whilst incorrectly predicting the geology. Therefore a low misfit does not necessarily indicate a good solution for 1D. The 2.5D method is a least-squares best fit of the observations and so the quoted misfit for 2.5D is a very different measure than for 1D.

The study demonstrates that 2.5D yields a much more satisfactory geology section and a better reconciliation with information contained in the survey data.

OTZE – AIRBORNE EM INVERSION ON UNSTRUCTURED MODEL GRIDS

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An efficient, accurate, multi-grid algorithm has been implemented for the modeling of airborne, land and marine controlled source electromagnetic data, providing accurate 3D depth inversions of frequency and time domain data with cost-effective compute timelines.

The forward kernel can either be a 1D solver for layered models, or 2.5D or 3D solvers based on a finite difference approach. The inverted resistivity model mesh is constructed from rectangular cells similar to conventional finite difference approaches. While these cells form a standard rectilinear grid in the horizontal plane, vertically they can be arranged arbitrarily. This vertically unstructured nature of the model grid requires a mapping to the finite difference grids, which is performed on-the-fly in the solver.

This feature, together with an appropriately arranged smoothness constraint, is useful in a variety of workflows. It helps in the presence of topography and also can be used to incorporate general *a priori* information about the survey area for blind inversions, as well as specific structural information for hypothesis testing. However, the potentially complex model geometry requires changes to some of the other available regularisations like the cross-gradient operator which is used to include for example surface geology dip and strike observations or for joint inversions with gravity gradiometry or magnetics.

We discuss the technical aspects of the implementation, illustrated with example workflows from diverse applications: stand-alone AEM inversions, joint inversions including frequency and time-domain EM.

REALISTIC EXPECTATIONS FOR DEEP GROUND PENETRATING RADAR PERFORMANCE

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Ground penetrating radar (GPR) is unique amongst geophysical tools in its diversity of applications and imaging resolution. Since its commercialisation four decades ago, GPR has also been unique in the prevalence of some of its purveyors to oversell the method's capabilities, relying largely on the end users' lack of understanding. Early adopters in the 1980s and 90s were dismayed to find that environments suitable for its purported ubiquitous deep penetration capabilities were rare, and required resistivities well into the 1000s of Ohm m. Regardless of advances made in electronics and antennas design, the fundamental limitations have not changed.

Misconceptions, 'specsmanship' and hype continue to abound in the GPR marketplace, particularly in recent years. Systems purporting to penetrate hundreds of metres using 'megawatt' transmitters from the former Eastern Block have been promoted for mineral exploration, particularly in Australia and Africa. Other pseudo-radar concepts, such as the use of beam forming to achieve kilometres of penetration with centimetre accuracy, or THz laser scanners which can detect individual diamonds deep underground have generally targeted junior exploration groups who lack in-house geophysical guidance.

This work will overview the fundamentals of non-dispersive EM wave propagation in the ground, and will examine the recent published performance claims of some GPR and pseudo-GPS systems within the context of accepted EM theory. Also discussed will be accepted methods of potentially increasing GPR performance given emerging technologies, such as very low-cost systems, phased-array radars, novel transmitter and receiver designs, and new GPR antennas.

1345–1500
MONDAY 19 FEBRUARY 2018

2F EXPLORATION

UNDERSTANDING GEOLOGY AND STRUCTURE: AN ESSENTIAL PART OF MINERAL RESOURCE ESTIMATION

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The JORC Code states that assumption of continuity of mineralisation between sampling points, requires a "*confident interpretation of the geological framework*". The elements of relevance to a geological framework vary greatly depending on the commodity and style of mineralisation. In general terms, at least two elements must be considered to underpin a geological framework: space and time.

The geometry and location of a mineralised body are controlled by physical and/or chemical elements, which can be unraveled by sound geological mapping, adequate geochemical and structural interpretations and by 3D geological modelling. These elements may involve, among other, aspects of stratigraphy, chemical or physical properties of the rocks and structural features such as faults, fractures and folds.

Mineralisation events that lead to economic deposits are often relatively short-lived periods of focused fluid transfer and element-exchange, which result in mobilisation and deposition of metals in well-defined areas. Understanding the temporal framework of structural elements and mineralising events results in the development of more accurate geological models and can lead to predictive capabilities that can result in new discoveries.

We present case studies in regional metamorphic, igneous, sedimentary and surficial geological environments, demonstrating how understanding the mineralisation system not only results in increased confidence in the Resource, but also facilitates reduction of exploration risks.

BUILDING 3-D MODEL OF ROCK QUALITY DESIGNATION ASSISTED BY CO-OPERATIVE INVERSION OF SEISMIC AND BOREHOLE DATA

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Rock quality designation (RQD) is an important factor for geo-techniques in mining production. RQD is defined by the percentage of total length of core pieces that is greater than ten centimetres in the total length of core run. This factor is influenced by rock properties such as fracture and hardness. In nature, the fracture and hardness of the rock also relate to seismic velocity. Thus we can use the seismic information to build an RQD model if we can define the relationship between RQD and seismic velocity. This model is significant for mining design. In practice, the mining design needs information of the whole mine area, but, the borehole is localised valuable. Meanwhile, the surface seismic method can provide information of the whole survey areas, but the resolution is smaller than the borehole data. The seismic and borehole data may provide very useful information for geo-techniques if we can exploit seismic data as a mean of interpolating the borehole data to the whole model of geo-techniques factor like RQD. In this work, we analyse borehole data to establish the relationship between RQD and seismic P-wave velocity. This relationship is used to convert 3D seismic model that obtained by co-operative inversion of seismic and borehole data into a 3D model of RQD.

1345–1500
MONDAY 19 FEBRUARY 2018

2G REGIONAL TECTONIC

EVOLVING 3D LITHOSPHERIC RESISTIVITY MODELS ACROSS SOUTHERN AUSTRALIA DERIVED FROM AUSLAMP MT

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The Australian Lithospheric Architecture Magnetotelluric program (AusLAMP) is a continent-wide deployment of long-period (10–10 000 s) MT instruments roughly every 50 km to map the electrical resistivity structure of the Australian continental lithosphere. The coverage of sites in South Australia is nearing completion with large funding from SA's Pace initiatives and in collaboration with the University of Adelaide and Geoscience Australia (across the Maralinga-Tjarutja Lands). We present the latest 3D resistivity models of the state across the southern two-thirds of South Australia. The area covers the Archean-Proterozoic Gawler craton, and its western and eastern margins, extending across to the east and covering the Flinders Ranges and Curnamona Province. The central Gawler Craton is imaged as a resistive zone with conductive margins surrounding the core of the cratonic block. Contrary to seismic tomography models, showing a fairly homogeneous and fast velocity structure, the Curnamona Province shows a highly heterogeneous resistivity distribution with low resistivity zones in the crust beneath the Province. Currently, the AusLAMP grid in South Australia is expanding across the NE of the state in the Cooper Basin and the Simpson Desert, an area that has not been covered by any deep-probing geophysical techniques. We aim to also present preliminary results of this extension.

The results of the inversion of the AusLAMP data highlight the correlative significance with other geochemical data and points towards MT as a geophysical fertility vector for mineral discovery.

IMPRINTS OF TECTONIC PROCESSES IMAGED WITH MAGNETOTELLURICS AND SEISMIC REFLECTION

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Co-located seismic and magnetotelluric (MT) profiles provide fundamental geophysical data sets to image the crust of Australia. Despite their overlapping nature, the data are processed and interpreted separately based on legacy workflows. We qualitatively compare 2D resistivity inversion models derived from MT and uninterpreted seismic reflection profiles across Proterozoic Australia to address the long-standing cross-cutting nature of interpreted seismic faults and low resistivity zones derived from MT. We find that a good correlation exists between high/low reflectivity in seismic sections and low resistivity in MT sections. These relationships elucidate signatures of past magmatic and fluid-related events and constrain zones of weakened rheology in the crust. Depending on their characteristics, these signatures may signify fossil melting of the crust due to underplating or magmatic invasion into the crust or reworking associated with redistribution of fluids along newly developed faults. These findings have implications for constraining mineral deposit genesis and location.

IDENTIFYING LITHOSPHERIC BOUNDARIES AND THEIR IMPORTANCE FOR MINERAL DISCOVERY

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Domain boundaries under cover have commonly been recognised through tracing of potential field anomalies such as extensive magnetic boundaries representing margins of upper crustal packages in conjunction with density contrast. Here, we extend the investigation of domain mapping to include isotope geochemistry and deep-probing magnetotelluric data. These data sets map the deeper crustal and mantle lithosphere. We demonstrate with examples across the Kalinjala Shear Zone, South Australia, and the Eastern Gawler craton, that major lithospheric domain boundaries exert a primary control on the location of mineral deposits near the surface.

We show examples of correlating of magnetotelluric models derived from the Australian Lithospheric Magnetotelluric Project (AusLAMP) and higher density broadband magnetotelluric deployments along profiles with isotope geochemistry across major lithospheric boundaries in South Australia. As one

example, the Kalinjala Shear Zone in the southern Gawler craton can be better constrained using the additional geochemical and magnetotelluric data sets and solve a long-standing debate about the northern extension of the Kalinjala Shear Zone towards the prospective Olympic domain hosting major IOCG deposits. These insights motivate future exploration programs which focus on in-fill broadband deployments for MT and isotope mapping to trace the lithosphere boundaries to the surface to reduce risk for mineral exploration.

1345–1500 MONDAY 19 FEBRUARY 2018

2H GEOTECHNICAL AND ENVIRONMENTAL

HOW TO BUILD YOUR OWN SIMPLE, LOW-COST, SEISMIC SYSTEM

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Acquiring seismic data has typically been an expensive pursuit due to the high price of the acquisition systems. Such systems are also typically not easily adaptable to suit different acquisition scenarios. In this paper we detail the manufacture and performance of an easily adaptable, low-cost (~$40/channel), seismic acquisition system. Data recorded using the system is comparable to that obtained using a far more expensive commercial seismograph.

Seismic sources are similarly expensive with the only low-cost option being a sledgehammer. In the second part of this paper we describe how to manufacture a small vibroseis unit from easily available components at a cost of less than $3000. This unit has a wider, more controllable, bandwidth than an impact source and can be easily adapted to create a shear wave source for MASW surveys.

FEASIBILITY STUDY OF NEAR-SURFACE DISPERSION IMAGING USING PASSIVE SEISMIC DATA

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Multichannel Analysis of Surface Waves is a seismic technique used to define the near-surface structures and rock properties. It has been vastly used through active seismic surveys for seismic/geotechnical engineering as well. It can also provide information about regolith heterogeneity that is of relevance to reflection seismic data processing. However, active surface wave investigations are not always possible due to site restrictions and environmental constraints. In this research, we studied the feasibility of passive seismic for the analysis of surface waves caused by different type of ambient noise and ground motion. The example presented comes from a data set collected over a hard-rock environment. We showed that the achieved results from passive data have a considerable correlation with the results from active data of the same acquisition survey.

REFRACTION MICROTREMOR FOR DELINEATION OF LAYERS AND LENSES, AND ASSESSING LIQUEFACTION POTENTIAL WITHIN AN ALLUVIAL SETTING – MOROBE PROVINCE, PAPUA NEW GUINEA

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Refraction Microtremor (ReMi) is a relatively new method in the geophysics industry. ReMi provides high resolution seismic shear wave velocity models up to 200 m depth and as such has the potential for being an efficient method for assessing the soil liquefaction potential in seismically active regions.

This paper presents a geophysical investigation carried out as part of a geotechnical feasibility study for a proposed Tailings Storage Facility (TSF) in the Morobe Province of Papua New Guinea. The primary objective of the investigation was to use geophysical methods to obtain subsurface parameters to assess the liquefaction potential within an interbedded and lensed clay/gravel alluvial setting. ReMi together with down hole and cross hole seismic methods were used to generate shear wave velocity information of multiple layers with depth, and in particular to define seismic velocity inversions.

ReMi data was acquired using two array setups specifically targeting the top 100 m of subsurface material and the top 50 m of subsurface material at increased layer resolution. The data was inverted to produce shear wave velocity soundings which were correlated with the cross hole and down hole seismic methods, and with borehole Standard Penetration Tests (SPT). The soundings were compiled to generate high resolution shear wave velocity sections, analysis of which proved pertinent in defining the interconnectivity of the lensed clay/gravel and shear wave velocity variations for the calculation of liquefaction potential thresholds.

1530–1710 MONDAY 19 FEBRUARY 2018

3A COAL

COOPER BASIN DEEP COAL – THE NEW UNCONVENTIONAL PARADIGM: DEEPEST PRODUCING COALS IN AUSTRALIA

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Up to three years of gas production from Permian-aged coals, in the SA Cooper Basin has exposed them as a potentially sustainable unconventional gas resource. The success of this play is a result of many years of research, laboratory tests and field trials to de-risk the play, following a well defined road-map.

Since 2012, production variability has been tested in over 50 wells across the SA Cooper Basin. As an add-on frac stage in a conventional gas development well, coal targets are regularly yielding incremental reserve. This is providing an uplift in

production and the opportunity to access a new tranche of gas. Production from the coal reservoirs is now accepted as 'base-business' for the Cooper Basin Joint Venture partners.

The key to progressing the play from its earliest inception to a productive reservoir, lies in a focused approach to de-risking each economic barrier. These risk factors include frac containment, formation water production, gas composition, permeability, deliverability, completion design and cost.

Next steps are to prove economic viability of deep coal as a stand-alone development. In these projects, planned for late 2017 – early 2018, both vertical and horizontal completions specifically targeting deep coal will be tested for commercial flow rates in existing productive fields.

PREDICTING STRUCTURAL PERMEABILITY IN THE DEEP COAL PLAY, TIRRAWARRA-GOORANIE FIELDS, COOPER BASIN

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The Tirrawarra-Gooranie oil and gas field complex in the Cooper Basin, South Australia has produced from a large number of vertically stacked conventional and unconventional targets. The unconventional Permian coal seams remain largely untapped, with only a limited number of hydraulic fracture stimulation trials commingled within conventional vertical wells. Variability in the coal zone frac treating pressures, gas rates and EURs has been observed. This is thought to be driven by variability in the in-situ reservoir properties; local stress field; occurrence of natural fractures; stimulation design and the interaction between these factors.

In a 2D study, a numerical stress model based on the distinct element method (DEM) was applied to a rigorous structural framework model, in order to understand how paleo- and present-day regional stress fields have interacted with faults in the Tirrawarra-Gooranie structure at the Patchawarra VC40/50 coal horizon. Areas of high differential stress are interpreted to be more prone to natural fractures, which may improve the coal productivity but may also require different stimulation treatments to areas with lower permeability. The model was calibrated against well data including 1D mechanical earth models, fracture initiation pressures, image logs and drill cores. Predicting areas of enhanced structural permeability using DEM is shown to be useful for early stage appraisal of unconventional reservoirs requiring large amounts of hydraulic fracture stimulation, and is also informative in helping to predict potentially problematic areas with higher breakdown and treating pressures.

TOWARDS UNDERSTANDING PHOSPHORUS DISTRIBUTION IN COAL: A CASE STUDY FROM THE BOWEN BASIN

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In coal phosphorus can occur in a variety of minerals but fluorapatite $Ca_5(PO_4)_3F$ is the most common. This mineral is often observed within the cell-lumens of inertinite macerals and interpreted as an early diagenetic mineral phase, although fracture-infilling fluorapatite has also been reported. Its small size and predominant occurrence within the cell lumens of the inertinite group macerals, means the fluorapatite cannot easily be liberated by current coal beneficiation strategies. Its occurrence may also reduce porosity and clog flow paths for gas drainage.

Understanding the spatial distribution, which reflects the origins and geological history of the coal and fluids moving through it, assists in developing mitigation strategies. The compilation and spatial analysis of elemental data within Permian coal deposits in different structural settings in the Bowen Basin provides the framework in which samples were collected and analysed by microscopic and spectroscopic techniques.

Preliminary results in the study area show elevated phosphorus contents are common in the roof and floor of the coal seam. However, these contents transgress lithotypes, up-dip along the flanks of an anticline, proximal to a fault, a dyke and sill and a rider seam split. At least two apatite mineral phases have been identified: cell-lumen- and fracture-infilling. However, a relationship between mode of occurrence and proximity to geological structures has not yet been observed. Although mode of occurrence appears to be indiscriminate, the analysis performed on phosphorus contents suggests a relationship between spatial distribution and geology. This infers that geology could be used to predict *in situ* elevated phosphorus contents within coal.

EVIDENCE FOR GLACIAL AND POLAR IMPACTS IN THE PERMIAN COAL MEASURES OF THE SYDNEY BASIN

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Since the 1840s, geologists have speculated about the degree and timing of contributions by glacial processes in the formation of the Permian coal bearing and marine sequences of the Sydney Basin. Unambiguous classical glacial evidence occurs in the underlying Carboniferous but later Glendonites and dropstones were seen only as contributions from cold water and floating ice.

Continuing improvement in the resolution of the 'polar path' throughout time, place the Sydney Basin at latitudes of 75S to 90S from the Early to Late Permian (Klootwijk 2016). Current evidence of climate change and its influence on glacial environments demonstrate there is more evidence of glacial processes in the Permian coal measures themselves.

Major elements, of the Newcastle Coal Measures are suggested to have glacial signatures and the Sydney Basin coal seams themselves display enigmatic properties that are suggestive of high latitude 'interglacial' environments. The Teralba and Bolton Point Conglomerate strata, shown in the 1980s to form elongate, high energy, channel like, coarse clastic deposits, sit enigmatically in the supposedly flat and marshy coal forming environments. A coal forming model of freshwater lakes with 'Gilbert' deltas, (Conaghan 1981) is revisited but with compelling current global evidence. Recent observations in the Arctic, of waning ice sheets and melting processes clearly illustrate 'moulins', sub-glacial drainage and their links to 'tunnel valleys' and 'eskers'.

A high latitude, cyclical, glacial model for coal measure formation is suggested, which is similar to that now discernible

in recent Arctic landforms. The required time scale and cyclicity are supported by Permian CA IDTIMS zircon age dating.

1530–1710
MONDAY 19 FEBRUARY 2018

3B WEST AUSTRALIAN BASINS SYMPOSIUM

INFLUENCE OF PERMIAN AND CARBONIFEROUS EXTENSIONAL HISTORY ON THE NORTHERN CARNARVON BASIN AND ITS INFLUENCE ON MESOZOIC EXTENSION

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The North-West Shelf of Australia is a marginal rift system related principally to the fragmentation of Gondwana. Permian-Carboniferous structures along the margin have long been recognised as fundamental events responsible for the formation of the offshore basins that comprise the prolific hydrocarbon producing region. However, the tectonic setting in which this rifting occurred remains unclear.

Detailed mapping of the geometry of Permian and Carboniferous structures on the southern margin of the Carnarvon Basin is possible using regional scale interpretation of publically available 2D and 3D seismic data. Seismic interpretation, combined with 2D structural reconstruction of major faults reveals two distinct orientations of structures. NNE trending faults were initiated in the Carboniferous or Devonian but were underfilled, resulting in erosion of the fault block crest and filling of the remnant rift-related topography by conformable sequences of later Permian and Triassic sediments. By contrast, NE-SW oriented faults experienced a distinct phase of Permian activity and are unconformably overlain by Triassic sediments.

This older rift architecture has clearly affected the geometry of the subsequent Upper Triassic to Middle Jurassic rift and can account for the en-echelon style of faulting on the northern margin of the Dampier Basin. Reactivation of the eroded fault block crests results in complex fault geometries and significant deformation of hanging wall strata during Mesozoic extension. The crustal scale geometry of these fundamental faults may also account for the unusual nature of the Lewis Trough in which the syn-rift sequence forms a broad syncline, rather than the more typical rotated fault blocks and syn-rift wedges.

INTERPRETATION OF A PERMIAN CONJUGATE BASIN MARGIN PRESERVED ON THE OUTER NORTHWEST SHELF OF AUSTRALIA

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The Northwest Shelf (NWS) of Australia is characterised as a series of northeast-southwest trending Mesozoic offshore depocentres which both juxtapose and partially overprint a series of onshore, northwest-southeast trending Paleozoic basins. An integrated interpretation of well bore data, regional seismic data and plate tectonic models suggests that the Paleozoic section is also present below the Mesozoic depocentres. Referred to as the East Gondwana Interior Rift, the primary rift axis is oriented in a (present day) NE–SW direction, below the Mesozoic section, with orthogonal marginal rift basins such as the onshore Canning and Southern Carnarvon basins.

While precise age dating for the initial formation of the axial rift is speculative, our integrated interpretation suggests that a significant portion of the pre-existing rift was modified by a Mid-Permian extensional event, forming the Northern Carnarvon basin. Interpretation of recent acquired 3D reflection seismic data suggests that the conjugate basin margin from this Permian rifting event is preserved, and is visible below the Mesozoic section. A series of back-stepping, Late Permian carbonate ramps and banks is interpreted to form on a thermally subsiding rift flank. Our interpretation of these carbonate banks is based primarily on seismic geometries, and is supported by area well control and regional paleogeographic models.

This interpretation suggests that deep marine intra-continental basin bisected the NWS in the Late Permian. Then shallow marine conditions persisted across the conjugate margin through the Triassic and into the Jurassic. Only after Late Jurassic rifting associated with Gondwanan break-up, did the region subside into deep water.

NEW INSIGHTS INTO EARLY TRIASSIC RIFTING IN THE NW SHELF HELP EXPLAIN REGIONAL STRUCTURAL STYLES AND ASSOCIATED DEPOSITION MODEL

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The offshore Canning is an amazingly complex and unexpected piece of geology. Large seismic geometries appear to be lava deltas associated with a rift volcanic complex. Gravity and magnetic modelling can be shown to support this geological model and its apparent thickness of up to 8 km in places. This is therefore volumetrically comparable to global end-Permian flood basalts analogs such as the Siberian and Emeishan traps.

The location of this outpouring can potentially be associated with a failed triple junction. The impact of this rifting is felt regionally. Syn-rift growth faulting is easily identified and can be shown to extend along a Northern rift arm up to the proto-Barcoo and proto-Caswell sub-basins. Strike-slip motion, previously known as the Fitzroy movement, along the eastern rift arm propagates through the Fitzroy Trough creating the numerous trans-pressional and trans-extensional features. Uplift along the third Western rift arm, to the north of Wombat plateau, sets up the elliptical bowl like geometry of the Northern Carnarvon basin that is clearly visible from an isopach of the early Triassic. This uplift also helps to explain the long-lived shallow marine Cossigny limestone and the expected sudden influx of eroded clastic sediment into the Northern Carnarvon basin can be tied to a large prograding Triassic shelf visible on 2D regional seismic data.

This large volcanic province may help explain the small percentage of Triassic-aged detrital zircons found throughout the Triassic Mungaroo formation.

This paper highlights Woodside's view that a regional approach, incorporating data from multiple sources, geographical areas and formations, assists with our broader understanding of tectonic history of the North West Shelf during the Early Triassic to Middle Triassic.

MODELLING RESERVOIR DELIVERABILITY WITHIN THE NORTHERN BEAGLE SUB-BASIN, WESTERN AUSTRALIA

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Reservoir deliverability* is a critical component affecting the viability of petroleum systems within a sedimentary basin. Calculating deliverability relies on estimates of reservoir pressure, permeability and thickness as well as fluid viscosity, all of which are difficult to predict in a frontier basin. Burial and erosional processes exert a fundamental control on these rock and fluid properties. If this erosion is not uniformly distributed across an area then complex variations in deliverability may result. This paper presents a novel approach to quantifying predictions of reservoir deliverability within the Northern Beagle Sub-basin of Western Australia, via the use of a 3D basin-scale model that provides spatial and temporal estimates of variations in rock and fluid properties.

Active extension began in the Northern Beagle Sub-basin during the Early Jurassic and resulted in deposition of proposed source and reservoir intervals. A thick (>5 km) succession of progradational Middle Jurassic deltaics overlies the early Jurassic petroleum system. During the Late Jurassic, the basin underwent a complex phase of erosion (attributed to rift flank uplift), which resulted in upwards of 3 km of sediment being locally removed on footwall blocks of active faults, as well as over structural highs. In other areas, however, such as contemporaneous structural lows, amounts of erosion are minimal. This complex spatial pattern of erosion has implications for both the thermal history (affecting fluid viscosity), as well as reservoir quality (permeability).

The final product generated from this workflow was an integrated, basin-scale 3D model of reservoir deliverability for the Northern Beagle Sub-basin.

* Reservoir Deliverability $\boldsymbol{Q} = (\Delta \boldsymbol{p}\ \boldsymbol{KH})/\boldsymbol{\mu}$, where

$\Delta \boldsymbol{p}$ = Reservoir Pressure – Surface Pressure

$\boldsymbol{K}$ = Reservoir permeabilty

$\boldsymbol{H}$ = Reservoir Thickness

$\boldsymbol{\mu}$ = Fluid viscosity

1530–1710
MONDAY 19 FEBRUARY 2018

3C EAST AUSTRALIAN BASINS SYMPOSIUM

PETROLEUM PLAYS OF THE BOWEN AND SURAT BASINS

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A petroleum play is an exploration concept that groups fields together based on similar characteristics, generally lithological or structural, that can be applied at regional or local scales. Conventional plays can be grouped by style of trap and geological region, or by target formation. Unconventional reservoirs, require a more complex approach to play based exploration, through mapping of several, highly variable characteristics and identification of 'sweet spots'. Examination of play characteristics and their spatial distributions can highlight areas that may contain new exploration prospects. This paper will review and summarise the types and distribution of petroleum plays in the Bowen and Surat basins. Since the 1960s, conventional exploration has targeted a number of different play types in the Bowen and Surat basins, varying from structural and stratigraphic traps on structural shelves and the flanks of the Taroom Trough, to coal seam gas, and, deep unconventional plays. Each of these are typically restricted to a geographic region (e.g. the Roma Shelf), or within a fairway (e.g. the Walloon Coal Seam Gas fairway). There is a general trend over time towards discoveries being made in older, deeper or more technologically challenging units. Extensive exploration and development has defined coal seam gas fairways in the Bowen Basin coal measures and Walloon Coal Measures. New exploration has examined tight or basin centred gas in the deep Taroom Trough.

BOREHOLE GRAVITY IN HORIZONTAL WELLS

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In response to current horizontal well technology, the latest borehole gravity logging tools are now capable of measurements in wells deviated from vertical to past horizontal. Historically oil and gas field borehole gravity data have been presented in the form of deep investigation, through casing, density logs, where the borehole gravity density is proportional to the vertical gravity gradient. This provides an excellent way to measure total porosity in heterogeneous carbonate reservoirs due to the large sampling volume. However the simple BHG density calculation is no longer applicable in horizontal wells and the data are similar to surface gravity profiles with differences due to being imbedded within or in close proximity to the target horizons.

Data acquisition in highly deviated wells brings new challenges largely associated with tool positioning. One mode of running the tool involves using a tractor to push the tool to the end of the well and then pulling back along hole to pre-set station locations. This can result in noticeable cycles of tool sticking and then rapid up-take, making it challenging to place a tool accurately at a pre-determined location.

Data processing for highly deviated BHG well logs has to take into account the well geometry to establish accurate 3 dimensional coordinates for each gravity station. Latitude corrections and terrain effects also assume more significance.

Time lapse monitoring of gravity changes in can be made much closer to or within the reservoir. The difference signal between logging runs is then solely due to the changes in the reservoir fluids or changes in porosity associated with formation fracturing. Data from single logging runs are influenced by all surrounding rock formations.

THE STRATIGRAPHIC SIGNIFICANCE OF PARALIC DEPOSITS IN THE PRECIPICE – EVERGREEN SUCCESSION, SURAT BASIN, QUEENSLAND

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The Precipice Sandstone and Evergreen Formation in the Surat Basin, Queensland, are being examined as a reservoir-seal target for future geosequestration of CO_2. Effective reservoir modelling, and prediction of dynamic storage capacity, however, depends upon accurate depositional interpretations and an understanding of stratigraphic architecture. Throughout most of the basin, the Precipice Sandstone is freshwater-bearing, attesting its reservoir properties and lateral continuity. Refined depositional models and a widely applied sequence stratigraphic framework will enhance prediction of the most prospective play segments for CO_2 injection.

We utilise integrated ichnological-sedimentological facies analysis from core to interpret the Precipice Sandstone as a fluvial/alluvial to delta plain succession, overlain by estuarine embayment deposits of the Evergreen Formation. Facies maps, based on core-calibrated wireline logs show brackish-water influenced deposits at several stratigraphic intervals. Brackish-water influenced deposits conformably overlay braided and meandering fluvial sediments, and generally cap parasequences. Seismic surveys resolve lower-order cyclicity, showing parasequence sets within the Precipice succession back stepping and aggrading. This stratal arrangement reflects the lowstand and early transgressive systems tracts. Late transgressive and early highstand systems tracts comprise the lower part of the Evergreen Formation.

Depositional and sequence stratigraphic interpretations suggest the precipice sandstone has a higher degree of reservoir compartmentalisation than previously appreciated. Moreover, we show that the Evergreen Formation is not a simple basin-wide sealing unit due to the presence of sandstone geobodies that may act as vertical fluid conduits. The sequence stratigraphic characteristics of the reservoir-seal pair should be carefully considered when selecting locations for CO_2 sequestration.

NEXT GENERATION RESERVOIR ENGINEERING

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Our mission is to advance knowledge about energy in transition with the aim to aid the industry in the imminent energy transformation. To this end we use an approach based on developing a fundamental physics based understanding of the chemical, mechanical, thermal and hydrological processes and their interactions that operate over long time scales to form and characterise the porosity/fracture networks in conventional and unconventional oil and gas reservoirs. We apply that understanding to engineer that structure for the purpose of energy extraction and resource discovery. The interdisciplinary approach links geoscience, engineering and computational science disciplines with the result of providing a step change in exploration and exploitation technologies with significant reduction in onshore gas development costs without compromising OHSE or environmental protection and assurance.

Numerical simulation has played a pivotal role in the dynamic reservoir modelling and for testing competing hypotheses in complex, typically data-poor environments. Though our ability to rigorously describe key processes in petroleum reservoirs is still imperfect (in particular unconventional plays), there have been substantial advances over the past several decades. These advances owe mainly to the steady growth of computational power and the concomitant development of numerical models that have gradually minimised various simplifying assumptions. They include incorporation of more accurate description of the fluid chemistry and its multiphase evolution and fluid flow rock interaction, an increased ability to represent geometric complexity and heterogeneity, and faster and more accurate computational schemes. In collaboration with international partners we have prototyped a multiphysics, multiscale simulator based on the Open Source **M**assively **O**bject **O**riented **S**imulation **E**nvironment (MOOSE), originally designed for running synchronous multiphysics calculations for a nuclear power plant. The Multi App framework allows coupling processes at grain level through to the fission in the reactor core, including the large-scale fluid flow in the pipe network of the heat exchangers of the power plant.

In this presentation, we will show the first results that allow incorporation of important processes in unconventional plays. Surprisingly, diagenetic processes such as the smectite-illite transition are found to create natural fractures under tectonic load that form the permeable reservoirs in shale gas/oil reservoirs. Results indicate that the fractures triggered by natural fluid release reaction on geological time scales are supported by a critical fluid pressure that must not be crossed to avoid sudden loss of the reservoir. Upon crossing this threshold reservoir damage can be substantial. No amount of proppant or other engineering interaction can rescue the reservoir on a human time-scale. Our novel framework allows to link the long-time scale geological processes with the design of an injection-extraction protocol to maintain critical fluid pressure. We are also able to incorporate micro-structural changes and fluid-solid interaction at grain scale. The latter has only been benchmarked for conventional carbonate plays, but the Multiscale results are encouraging for the entire spectrum of conventional and unconventional traps/source rocks. Our theoretical framework and the forward simulator is specifically designed to interface

with geophysical inversion techniques for multi-scale geophysical data. Completing this data-assimilation step in the future will define next generation reservoir engineering.

1530–1710
MONDAY 19 FEBRUARY 2018

3D GEOLOGY CASE HISTORY

CARGO PORPHYRY CU–AU DEPOSIT – WHERE IS THE HIGH GRADE CORE?

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The Cargo Copper-Gold Porphyry deposit lies within the world class porphyry belt of Ordovician Macquarie volcanic arc. It is one of several porphyry complexes in Lachlan Orogen including Cadia Valley (42.8 MOz Au) North Parkes, Cowal and Copper Hill.

The Cargo Porphyry Intrusive Complex is a calc-alkaline suite of late Ordovician age (467 Ma) intrusive comprising quartz monzodiorite and diorite intruded by coeval andesitic and trachyandesitic volcanics. The most prominent NW trending structural zone is characterised by areas of strong silicification, pyritisation and tectonic brecciation together with stockwork and sheeted quartz veining. It is up to 300 m wide bounded on the southern side by a major 60° SW dipping normal on the northern side by 75° SW dipping shear zones.

Mineralisation and alteration is zoned from a western core of fracture controlled, potassic altered porphyry Cu-Mo-Au to a peripheral zone of phyllic altered gold rich quartz-sulphide veining up to 200 m wide, surrounded by an outer propylitic zinc rich halo.

The peripheral zone of Cargo contains gold rich sheeted quartz veins which hosted 14 small gold workings in the late 1800s. Two lode systems, Dalcoath and Spur, have JORC inferred resource of 4 Mt @ 1.19 g/t gold 154 000 Oz Au.

A classically zoned porphyry Cargo's geochemical footprint is comparable in size to the famous Bingham Canyon and the Bougainville Panguna deposit despite the fact that Cargo's porphyry deposit's western half has been faulted away.

IMPLICIT MODELLING OF THE LAS BAMBAS DEPOSITS, PERU

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The primary objectives of any 3D implicit geological model are to better visualise, understand, and demonstrate the data you have, to provide an environment fostering robust interpretation, to build on those interpretations and extrapolate into theoretical space, to quantify our economic variables, and to encourage the scientific method by allowing competing theories to be explored virtually, maximising discovery and expansion.

Recent advances in understanding MMG's Flagship project, the Las Bambas Mine, Apurimac, Peru, its mineralising system and analysis of the opportunities for expansion have been assisted by the construction of an implicit geological model that not only effectively demonstrates the major features of the system, but has provided a versatile experimental environment within which geological theories and generation of predictive geometries are constantly queried.

Las Bambas is a world class suite of Cu deposits in the high Andes. The system can be described as a series of Eocene igneous stocks, sills and dike swarms intruding lower cretaceous limestones of the Ferrobamba formation, resulting in the generation of garnet-pyroxene-epidote-magnetite skarns, which have mineralised through syn-epigenetic fluid interaction, filling voids and introducing chalcopyrite and bornite, with later molybdenite mineralisation.

In this presentation, the implicit model serves as an effective medium for illustrating the Las Bambas deposit geometries and mineralisation relationships, leading to analysis of near mine exploration opportunity.

WHAT IS DOWN PLUNGE OF THE DOBROYDE HILL HIGH-SULPHIDATION EPITHERMAL DEPOSIT, NEAR JUNEE, NSW?

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The Dobroyde Hill high-sulphidation epithermal gold prospect sits within the 4 km long calc-alkalic andesitic Dobroyde Volcanic Complex, 50 km north of Wagga Wagga and 10 km north of Junee and is in the southern section of the Junee-Narromine Volcanic Belt. The Hill was the focus of episodes of exploration from the mid-1970s until 1990. Revival of the Prospect came when recent drilling intersected carbonate base-metal style alteration with associated gold mineralisation and in another hole a package of younger conglomerates containing pebbles of mineralised quartz stockwork in altered porphyry.

These targets were derived by the recognition of widespread dickite, pyrophyllite, silica alteration during mapping, favourable IP and magnetic anomalies and barium geochemistry.

One of the holes was targeting 700 m down plunge from the high-sulphidation epithermal Dobroyde Hill mineralisation. This hole intercepted long intervals of carbonate base-metal epithermal alteration and wide low-grade mineralisation and shows some key similarities to the 8M Oz Cowal E42 gold mine owned by Evolution Mining. This is different in style to the high-sulphidation Dobroyde Hill mineralisation.

The newly intersected geology, alteration and mineralisation is interpreted to be the outer shell of a larger zone of mineralisation. Clay mineralogy suggests the hotter core of the deposit may be within a few hundred metres away.

When the calc-alkalic Dobroyde Volcanic Complex was forming, it is thought to have been long lived, multifaceted and the chemistry of the fluids evolved over time hence the Complex may have the potential to host one or more major deposits.

THE DISCOVERY OF THE EDNA BERYL DEPOSIT – A JOURNEY WITH A DESTINATION!

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Edna Beryl was discovered by prospectors in 1936 and mined underground until the closure of the mine in 1942. Mining recommenced at Edna Beryl in 1945–46 when several shafts and drives were developed to a maximum depth of approximately 50 m before encountering the water table. However it was not until June 2016 following a systematic exploration program by Emmerson, did the extent of the Edna Beryl mineralisation emerge.

Since inception, Emmerson's strategy has been firmly focussed on discovery from the implementation of a science-based approach to exploration but within a clear, risk-based business framework. Our technical approach includes integrating both the Prediction and Detection elements of our exploration model across all geological scales. With the assistance of Kenex Limited, we have adopted an objective, probabilistic targeting methodology, whereby target ranking is derived from a solid understanding of ore processes and their fingerprints – the critical step of turning data into information. No one data layer is definitive; rather the more robust targets are derived from multiple geoscientific data that are highly correlated to the mineralisation.

The application of various detection techniques are aimed at precisely pinpointing the location of the mineralisation for drill testing. The Au–Cu–Bi mineralised ironstones (generally hematite-dominant) are notoriously difficult to detect both from the geophysical and geochemical perspective. To date, Emmerson (and JV partners) have trialled gravity geophysics, a number of electrical techniques (including airborne EM), high resolution magnetics, and various geochemical techniques including ironstone fertility indices. The journey continues this field season with the testing of ultra-high resolution gravity and passive seismic methods.

In summary, Emmerson (and JV partners) have invested considerable resources in the Tennant Creek Mineral Field, all within a risk-based business framework and with the clear aim of discovery. We are increasingly confident that this approach will continue to be supported by our shareholders and provide a point of difference for retaining and attracting new joint ventures, such as at our recently acquired Rover and NSW projects.

1530–1710
MONDAY 19 FEBRUARY 2018

3E AIRBORNE GRAVITY

VALIDATING THE GEDEX HD-AGG™ AIRBORNE GRAVITY GRADIOMETER

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The Gedex High-Definition Airborne Gravity Gradiometer (HD-AGG™) was designed and developed to deliver measurements of the gravitational field with improved signal-to-noise and resolution. The system has been under development for more than 10 years and is approaching the point of commercial deployment. Knowledge of the gradiometer components being measured, noise character and resolution of the system will allow end-users to appropriately select exploration targets and to determine eventual survey parameters.

The validation of the Gedex system has been progressive in nature consisting of laboratory tests and flight tests in a Cessna Caravan after successive modifications. The lab experiments consist of static tests to establish the noise floor, signal confirmation tests and dynamic testing on a 6 degree-of-freedom shaker. The airborne testing includes high altitude flights to confirm the noise level and character of the system over long periods. Low-level flights have been carried out to establish resolution and noise levels under survey conditions. These have been conducted over areas where high resolution terrain data and ground gravity exists and geology is known. We present datasets from our validation program and discuss our path forward.

AIRBORNE GRAVIMETRY TAKES OFF IN THE WESTERN AUSTRALIA 'GENERATION 2' RECONNAISSANCE GRAVITY MAPPING PROJECT

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In 1974, the Australian Bureau of Mineral Resources, Geology and Geophysics completed a 15-year systematic reconnaissance gravity survey of Australia with stations spaced at 11 km. The 1976 Gravity Map of Australia was a seminal product; half a century later, the data still provide the only coverage for substantial parts of the continent.

In 2005, the Geological Survey of Western Australia, supported by Geoscience Australia, commenced a program of regional ground gravity surveys with 2.5 km station spacing, a sixteen-fold improvement of resolution over the 'first generation' BMR data. In 2013, GSWA declared its aim of completing 'second generation' reconnaissance gravity coverage of WA by 2020.

In 2016, with 45% of the State yet to be surveyed in the north and east, and ground access issues slowing progress and making uniform coverage increasingly difficult, GSWA and GA

undertook the first government-commissioned regional aerogravity survey in Australia, using the Sander Geophysics' AIRGrav system. The 38 000 line-km survey covering 84 000 km^2 in the East Kimberley was flown at 2.5 km line-spacing for compatible spatial resolution with GSWA's regional ground surveys.

We compare airborne with ground gravimetry in the context of the East Kimberley project and conclude that, for reconnaissance surveys: aerogravity costs now approach those of ground surveys; spatial resolution is equivalent; lower aerogravity precision is not a critical factor; and airborne and ground data can be merged seamlessly for interpretation.

Consequently, two new aerogravity surveys were undertaken over 264 000 km^2 of northern WA in the Tanami–King Leopold and Kidson regions.

GRAVITY GRADIOMETER DESIGN COMPARISON BY THREE DIFFERENT METHODS

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Two gravity gradiometer designs are currently available for commercial survey operations and other instruments are in the late stages of pre-deployment research. These gradiometer systems differ from one another with respect to the number and orientation of sensing accelerometer pairs. There is a need for a theoretical framework to evaluate how these design variations, affect the expected performance of these devices.

Three methods of design comparison will be presented: (1) Transformation of noise, a calculation of the degree of noise reduction produced by the method of transforming and combining measured gradient components. (2) Inversion errors, comparison of the degree to which noise induces errors in the values of parameters determined in a parametric inversion calculation. (3) Sensitivity, analysis of the response of each system to a point source and how that source varies as a function of location in 3D space. Each of these methods focuses on a different aspect of the practice of gravity gradiometry. Specifically, noise, inversion and source detection.

Analysis will be centered on comparison between the two gravity gradiometer designs manufactured by Lockheed-Martin. The full tensor gradiometer (FTG) and the horizontal partial tensor gradiometer that is part of the Falcon survey system. All three methods predict that in order for these two gradiometer designs to yield equivalent results the noise level of the horizontal partial tensor gradiometer must be less than that of each of the three sub-gradiometers of the FTG by a factor of 3.08.

AN OVERVIEW OF TENSORS, GRADIENT AND INVARIANT PRODUCTS IN IMAGING AND QUALITATIVE INTERPRETATION

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Potential Field Gradient Tensors are a multichannel dataset combining 5 independent components in a matrix array. As such, the data can be used and combined in many ways. A very common problem right across the world of geoscience is that even standard potential field transforms are not actually well understood by users. How does one expand grid transform concepts into the realm of tensors, where so many new combinations and concepts such as Invariants and Phase exist, and create lasting basis for industry interpretation?

It is important that all images used in potential field analysis carry some sort of physical meaning which is understood by the interpreter. True understanding arises from geophysically modelling a known 3D geological model, creating the grid transforms from the forward response of the model, and comparing these to the geology.

3D forward gravitational responses of a 3D model of a simple two-body basin-basement system with conjugate faulting and a dome-basin shape are used to generate the examples. Depths to the Basin-Basement interface were computed from the model and are presented as grids and contours draped on the gravity gradient imaging products to illustrate their responsiveness to the basement architecture.

Various combinations of traditional gravity and its gradient transforms, as well as tensor invariants and phase products, are assessed against the model. It is shown that certain imaging products show more responsiveness to physical property variations, whilst others are more sensitive to geometry, but combining these in novel ways can approach understanding of subsurface mapping possibly not explored previously using potential fields.

1530–1710
MONDAY 19 FEBRUARY 2018

3F ELECTRICAL METHODS

LABORATORY CONFIRMATION OF NON-LINEAR ELECTRICAL EFFECTS IN MINERALISED ROCKS

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A search for an exploration technique that was unique to sulphides, i.e. did not respond to graphite, clays and other polarisable materials, lead to the investigation of non-linear conduction in sulphides.

Early work in the 1960s indicated that non-linear effects were only detectable at high current densities, such as those found in borehole surveys.

When currents of two different frequencies are passed through a non-linear network, the resultant output contains the original two frequencies, harmonics of the two frequencies, and inter-modulation products of the two frequencies.

If the non-linearity arises at the semiconductor interface or junction then adding a direct current bias should increase the non-linearity to the extent it could be used in the field under normal field current densities of around 1.0 μA/cm^2. Work by previous investigators found the DC bias increased the effect 3 to four-fold.

Test work on core in the laboratory indicates that the effect is detectable at field current densities, although the measured inter-modulation products are 3 orders of magnitude less than the primary signal.

At CSIRO, recent laboratory based reinvestigation into non-linear properties of sulphides has been undertaken with a view towards field application. This study used modern electronics and signal processing to ascertain if this system could be viable in the field.

This presentation highlights some of the history, theory and problems associated with using non-linear conduction in sulphide mineralisation as an exploration tool.

FIELD TRIALS OF THE BIASSED HETERODYNE METHOD OF EXPLORATION OF EXPLORATION FOR SULPHIDE MINERALS

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The Biassed Heterodyne (BH) method uses the fact that sulphides are semi-conductors hence electrical junctions between sulphide grains can be non-linear in terms of current through versus potential across the junction. Other conductors in the earth such as electrolytic pathways, clays and graphite are likely to conduct electricity in a linear fashion. By galvanically transmitting two frequencies into the ground, intermodulation frequencies are generated in areas that have a significant proportion of non-linear conduction from sulphide minerals. These intermodulation frequencies should be able to be measured to map the subsurface location of sulphide bodies. Laboratory tests have shown the desired signal is extremely weak compared to the transmitted signals, and so a DC bias signal is also transmitted to enhance the heterodyne signal and aid in noise reduction.

Field tests of the method have been conducted at the Kempfield silver barite deposit near Bathurst NSW. The tests were conducted over an area of known massive sulphide mineralisation. Three IP transmitters were used for the primary and bias signals. These were arranged in a gradient array configuration. The two primary transmitters were run to produce 50 and 80 Hz square waves such that the difference heterodyne frequency of 30 Hz lies in the minimum between telluric and sferic natural noise. The bias transmitter is a standard castle waveform IP transmitter operating at 0.03125 Hz (8 second pulses). The primary signals are transmitted by modified GGT 30 Zonge IP transmitters. The receiver is a high sensitivity, high dynamic range A to D converter and spectrum analyser.

It is hoped that processing of the data can use the difference in heterodyne signal between the different periods of bias signal, such as the difference between positive and zero bias, to reduce noise to a level such that the difference intermodulation signal can be seen above the noise and thus be used to map subsurface sulphide minerals.

GETTING A BETTER CONTROL OF IP DATASETS WITH GDD'S NEW IP POST-PROCESSING SOFTWARE

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There used to be a time when an entire Resistivity/IP acquisition day had to be re-surveyed; wrong survey parameters had been set, timing errors had occur, repeatability of readings was poor, etc. This frustrating outcome was partly due to the impossibility of accessing full wave data and/or the lack of post-processing tools provide with geophysical instruments. For both ground and borehole EM and IP surveys, the situation remained a problem for a long time until recently some manufacturers have begun to offer access to the time series along with a software to thoroughly visualise and process the data.

Instrumentation GDD, a Canadian manufacturer of geophysical instrument since 1976, is one of them. The GDD IP receivers full wave data were accessible since 2009 but users can now use the new IP post-processing software. This presentation will include many examples of real data collected in different parts of the world for which it has been possible to: validate the nature of external noise to modify acquisition parameters and improve survey results, correct synchronisation off-set between the transmitter and the receiver, manually discard noisy half-cycle to recover data in specific cases for which the receiver algorithm did not perform well, enhance the apparent resistivity calculation using real-time current measurements at the transmitter controller, modify the Vs decay windows scheme in order to fine-tune chargeability responses in specific geological environments, and more.

THE EFFECTIVE USE OF FORWARD MODELLING AND PETROPHYSICAL ANALYSES IN THE APPLICATION OF INDUCED POLARISATION SURVEYS TO EXPLORE FOR DISSEMINATED SULPHIDE SYSTEMS IN THE PATERSON PROVINCE, WESTERN AUSTRALIA

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The Citadel Project is a JV between Rio Tinto Exploration (RTX) and Antipa Minerals extending over 400 km^2. The project is targeting disseminated and massive copper sulphide systems beneath 40 to 120 m of transported Permian cover with intermittent Cenozoic sand dunes. Dipole–Dipole (D–D) and Pole–Dipole (P–D) Induced Polarisation survey configurations were chosen as a cost effective method to prioritise the 16 target areas for drilling. Induced Polarisation (IP) survey traverses over the known gold–copper–silver±tungsten Calibre and Magnum deposits and the high grade polymetallic Corker deposit illustrated the effectiveness of the IP method for detecting mineralisation and led to a 127 line km D–D and P–D Induced Polarisation surveys being undertaken in the 2016 field season. The IP surveys highlighted multiple chargeablility anomalies along the Calibre structural corridor.

On completion of drilling, forward modelling of chargeability and resistivity data combined with petrophysical analysis of selected core samples provided a platform for testing geological concepts. In addition, it allowed the correlation of the

chargeability/resistivity data with drilling results, and the validation of inversion results.

In 2017 a new Induced Polarisation survey program has been planned to further delineate Blue Steel target and evaluate the Calibre structural corridor. In spite of well-known limitations associated with the Gradient Array configuration, combining regional AEM surveys with forward modelling was able to illustrate this method as a cost effective solution for exploring the Calibre structural corridor.

1530–1710
MONDAY 19 FEBRUARY 2018

3G REGIONAL GAWLER ISA HALLS CREEK

A HIDDEN PALAEOPROTEROZOIC OCEAN-CONTINENT TRANSITION IN THE NORTHERN GAWLER CRATON

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Craton margins are known to host many major deposit styles across the globe and, constraining the spatial and temporal relation between permissive geometries and thermal drivers for alteration processes, are key for identifying prospective terranes.

Orthogonal deep crustal reflection seismic profiles provide insight into the three-dimensional crustal architecture of the north-western Gawler Craton, South Australia. Correlating between north-south seismic line 08GA-OM1 and east-west seismic line 13GA-EG1, has enabled the interpretation of a major crustal boundary separating the core of the Gawler Craton from re-worked crustal provinces to the west and north. We use seismic character, potential fields and magnetotellurics to locate and constrain the geometry of this major boundary, and isotopic signatures from sparse drillholes to characterise the crustal age and composition either side of the interpreted boundary.

In recent years, isotopic evidence has been used to infer the presence of early Palaeproterozoic oceanic crust having existed between the Gawler and Yilgarn Cratons. We present a new model for the north-western Gawler Craton, locating a transitional region between a cratonic core and this oceanic crust, and suggest that the craton margin was ~100 km inboard of current interpretations.

THERMOCHRONOLOGICAL HISTORY OF THE NORTHERN OLYMPIC DOMAIN OF THE GAWLER CRATON; CORRELATIONS BETWEEN COOLING AGES AND MINERALISING SYSTEMS

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The Olympic Domain of the Gawler Craton is home to the world class Olympic Dam Iron Oxide Copper Gold (IOCG) mineral deposit in addition to numerous other IOCG mineral deposits. The Olympic Domain preserves a complex geological history that began in the Palaeoproterozoic. However, most published work conducted on these IOCG deposits have focused on their initial formation, with only a few studies investigating the post-formation thermal history of the Olympic Domain. This study uses multi-method thermochronology by combining apatite U/Pb, muscovite and potassium feldspar $^{40}Ar/^{39}Ar$, zircon and apatite (U-Th-Sm)/He, and apatite fission track (AFT) dating to provide insights into the thermal history of the northern Olympic Domain between ~550°C and surface temperatures. Apatite U/Pb and muscovite $^{40}Ar/^{39}Ar$ record post magmatic cooling of the ~1850 Ma Donington Suite, and ~1590 Ma Hiltaba Suite. Potassium feldspar $^{40}Ar/^{39}Ar$ analyses record a cooling signal that is likely related to rifting in the Neoproterozoic Adelaide Rift Complex. A combination of AFT, and zircon and apatite (U–Th–Sm)/He dating preserves three thermal periods, at ~1000 Ma, ~430–400 Ma and ~200 Ma. The older two thermal periods are interpreted to be regional cooling. However, the youngest ages are preserved closest to known IOCG deposits suggesting that they reflect cooling of this elevated geothermal-gradient crust in the Mesozoic. These results have been modelled to produce a thermal history map of the northern Olympic Domain.

TECTONIC FRAMEWORK OF THE SOUTHERN MOUNT ISA PROVINCE

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The North Australian Craton consists of a series of latest Archean to Paleoproterozoic cratonic blocks including a number of orogenic belts. The Mount Isa Province and the Tennant Creek-Davenport Province are two components of the North Australian Craton. They are interpreted to be adjacent in the undercover section of the southern Mount Isa Province. However, there is no current understanding of the tectonic architecture of this relationship. At best, conclusions drawn from studies of outcropping relationships can be extrapolated undercover.

This study uses recently collected magnetotelluric data, combined with deep crustal seismic, to directly investigate the relationship between the Mount Isa Province and the Tennant Creek–Davenport Region. The deep crustal seismic was

collected along two orthogonal profiles capturing the relationship between the two regions, while the magnetotelluric data was collected in a regional grid over the junction between seismic lines, extending further west. The MT data was inverted before being jointly interpreted with the seismic data and available potential field data.

Magnetotelluric inversion shows a highly resistive mid to lower crust beneath the Mount Isa Province. In contrast, the mid to lower crust for the Ardmore May Downs domain (Tennant Creek-Davenport equivalent) is broadly conductive, with several discrete features. This is consistent with other MT data collected to the north and west of the project area and indicates significantly different geology or tectonic histories between the two domains. The seismic data shows a major west dipping fault which is likely to be a crustal suture between the two Provinces.

MAGMA EVOLUTION IN THE HALLS CREEK OROGEN; INSIGHT FROM GEODYNAMIC NUMERICAL MODELLING AND GEOCHEMICAL ANALYSIS

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The two plausible tectonic scenarios of the Halls Creek Orogen are examined through 2D thermo-mechanical-petrological numerical experiments based on I2VIS code. The initial constraints for model setup are appropriate to the inferred tectonic environment for the protoliths to the Tickalara Metamorphics in an intra-ocean subduction or ocean-continent subduction/collision. These numerical models allowed us to examine the conceptual models of geodynamic setting scenarios of the Halls Creek Orogen through time. With this approach, we determined experiments with specific physical parameters that are compatible with the geology observed in the Halls Creek Orogen. Finding the model most compatible with the geology can reveal geological processes which are not observable without the aid of geodynamic simulation. The results indicate that the geology of the Halls Creek Orogen is best represented by the ensialic marginal basin scenario. A further aspect of the numerical models is the degree to which they reveal magmatic activities which lead in the generation of key lithological units during the tectonic evolution of the Halls Creek Orogen. Development and closure of a marginal basin and the role of collisional magmatism are important parts of tectono-thermal evolution of the Halls Creek Orogen. The numerical models predict magma sources through time, linked to the tectonothermal evolution of the region. Whole rock and isotope geochemistry from the region has been used to verify and improve the models.

1530–1710
MONDAY 19 FEBRUARY 2018

3H GROUNDWATER

USING MICROGRAVITY TO CHARACTERISE WATER STORAGE AND USAGE AT KINGS PARK, PERTH, WA

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Kings Park in Perth is a well-known urban parkland and tourist attraction, and is one of few urban parks to preserve extensive native bushland (evergreen woody vegetation). A key question in assessing ecosystem health is water availability and use, especially in periods of drought. Since March 2015 the UWA in collaboration with the BGPA has conducted a time-lapse microgravity study of groundwater storage in Kings Park. Data collection has focused on seasonal to inter-annual change, with bi-monthly measurements extending across multiple days. Relative measurements are taken with a Scintrex CG-5 gravity meter and are referred to the Helena Valley reference station, which is located in the granite-dominated Perth Hills. Interim results (May 2017) suggest that measurement methods are sufficiently sensitive to characterise change, with measurement precision of ±2 microgals (approximately ±40 mm of stored water).

Two-month storage-changes are defined from the gravity data, and usage is further defined as rainfall minus storage-change. Storage-changes are positively correlated with rainfall ($r = +0.70$) and negatively-correlated with solar exposure ($r = -0.69$). Thus, a fairly strong signal is seen of increase during the winter wet season, and decrease during the summer dry season. Usage is positively correlated with solar exposure ($r = +0.312$) but also shows dry periods in late summer, where estimated usage is near-zero despite high solar exposure, and a high-usage period at the start of the wet season. Interannual change is substantial, and seems to be linked to the Indian Ocean Dipole, which was strongly positive in winter 2015 and strongly negative in winter 2016.

MICROGRAVITY SURVEYS ON THE NULLARBOR

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A series of 15 microgravity surveys were undertaken by the Geological Survey of South Australia to determine if cavities existed underground in specific locations on the Nullarbor Plain, South Australia. Survey spacing ranged from 10 m to 20 m in a regular grid pattern. The grids were 200 m by 200 m in size, with additional traverses extending from the centre of each grid

in the cardinal directions, the total lengths of these lines being 600 m.

An additional survey undertaken over the Koonalda Sinkhole exhibited a 1.2 mGal magnitude anomaly. The remaining sites exhibited a range of magnitudes, peaking at approximately 0.5 mGal. The gravity images display areas of high and low density suggesting variation in the density of the limestone consistent with possible cavities.

The microgravity results have been used to aid a scientific drilling program in the area. The position of the drill rig was moved to areas exhibiting high gravity to reduce the chances of the drilling intersecting caves, and to reduce the chances of heavy trucks potentially breaking the surface and falling into a cavity.

UNCERTAINTY ANALYSIS OF FAULTING AND FOLDING ON NEAR SURFACE AQUIFERS

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With advances in near surface geophysical techniques, notably Airborne Electromagnetics (AEM), great strides have been made in mapping near-surface (0–200 m) hydrostratigraphy, including aquitards and aquifers. However, an important uncertainty in the mapping of groundwater systems and resource estimation is the potential impact of faults to:

- Generate fault parallel fracture transmissivity;
- Reduce across-fault permeability; and
- Provide connectivity from one aquifer to another across aquitards.

It is vital to differentiate between faults and fault propagation folds associated with 'blind faults'. As AEM is an evolving technology a set of criteria based on sound structural geomechanical and structural geologic has been developed to discriminate between faults and folds.

Even with consistent and robust modeling there are fundamental uncertainties that require appropriate modeling using stochastic fault seal analysis. An extensive database of calibrations has been developed for the prediction of liquid hydrocarbon free water levels (FWL). Based on hundreds of hindcasting models FWL can be predicted with better than 10 m accuracy.

Despite this high accuracy prediction the juxtaposition area of across fault reservoir vs reservoir juxtaposition can vary by two or three orders of magnitude. The juxtaposition area is a key term in the calculation of across-fault Darcy Flow. Variation in area is strongly nonlinear and dependent on accounting for the thickness of aquitards and variation along strike of fault displacement. It is vital that geologically valid faults are analysed with the appropriate parameter uncertainty. Examples from the Broken Hill Managed Aquifer Project and the Sydney Basin will be used to illustrate the process.

Accessibility, security key data management concerns, survey reveals

by VIRGINIA HEFFERNAN

The inability to find and access data via a single integrated search tool emerged as the biggest challenge for respondents to Geosoft's 2017 Geoscience Information Management Survey.

Consistent with Geosoft's past four surveys on the subject, the vast majority of respondents (83%) consider data management a critical or "top five" issue for their organization, compared with only 3% who consider it unimportant. But they continue to encounter challenges and barriers to success, especially how to find the data they need and keep that information secure.

Ranking of Data Management as an Issue

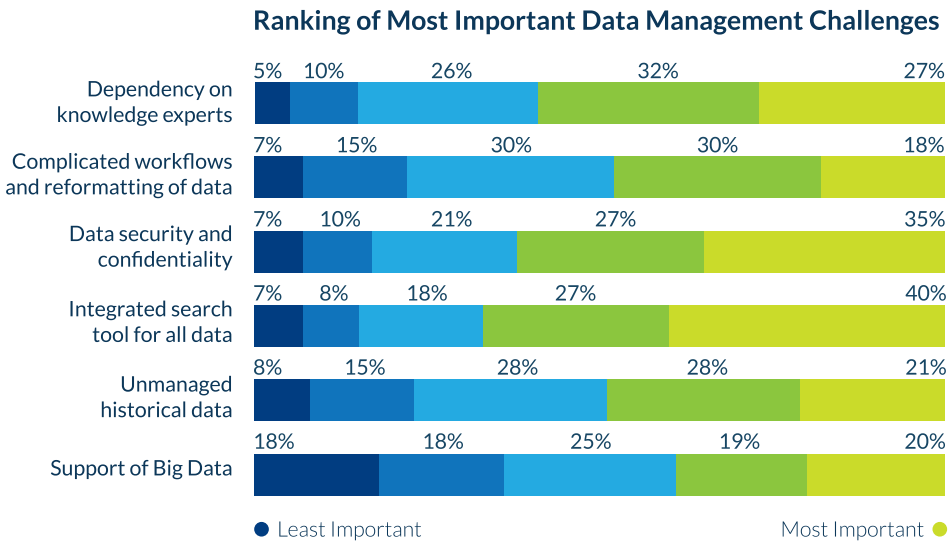
	2017	2015	2013
It is of critical importance	47%	48%	44%
Top 5 issue for our group	36%	37%	38%
On the radar, but not currently a focus	14%	12%	15%
Not important at this time	3%	3%	3%

This year, Geosoft received 1400 responses to the survey from 1000 organizations in 115 countries. Half of the respondents are from the mineral resources industry, while the remainder are from the government, energy, near surface or education sectors. Geoscientists – including geophysicists, geologists, GIS specialists and geochemists - represent 70% of the respondents. The rest identify as executives, managers, owners, data and IT administrators, teachers, researchers or students.

The top three most important data types for the participants were geological, geophysical and drill hole or well data. The majority manage this data either on their own or within a folder or file structure on a centralized server, rather than use a commercial solution. More than 60% are confident in the way their organizations handle the quantity and quality of data.

"It's promising that most respondents have confidence in their organization's current data handling, but being able to find and access all their data from a single search tool remains a challenge," says Ken Howieson, Geosoft's Vice President of Services.

In 2017 the survey was expanded with new questions to reflect the rising importance of the cloud and to gain a better understanding of the challenges organizations face when implementing a data management solution.



Here are some key observations:

Search tools need improvement

Asked to rank the comparative importance of data management challenges, respondents from all groups put the inability to find data through an integrated search tool at the top. Data security was a close second while dependency on knowledge experts also emerged as a pressing concern, especially for data administrators. By comparison, the biggest data management challenge in 2015 was the amount of unmanaged historical data.

Geoscientists spend valuable time managing data

Geoscientists spend 20-50% of their time managing data according to almost half of the respondents, time they could be devoting to other critical tasks such as exploration. In the 2015 survey, a quarter of the respondents did not know how much time their geoscientists spent on data management. But that number dropped to 11% in 2017, suggesting there is a growing awareness within organizations about the time and human resources required.

Culture and complexity outweigh cost as barriers

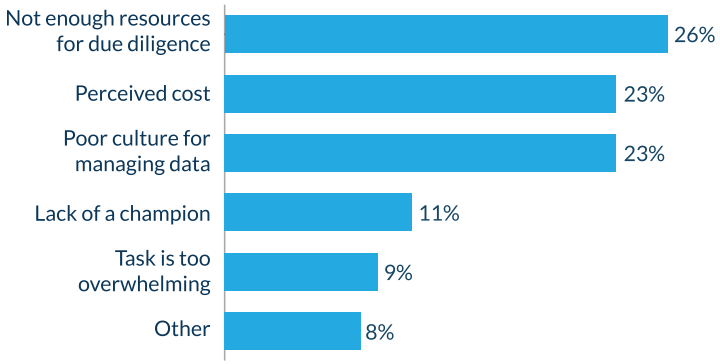
For the 2017 survey, Geosoft asked respondents what the main challenges are when selecting and implementing a data management solution. A lack of dedicated resources to complete due diligence, a poor culture for managing data and perceived cost are major, similarly ranked concerns. However, for the 47% of respondents who consider data management a critical issue, cost is less of a concern.

Most respondents would prefer to purchase an in-house (31%) or cloud-based (24%) solution while 24% - more among government and energy organizations – are inclined to develop and in-house proprietary solution. Only 12% would like to maintain the status quo, allowing end users to manage their own data, and 8% would outsource their data management.

Once a data management solution is in place, the complexity of integrating data silos becomes the main concern followed closely by the time and resources required to

maintain and fully populate the solution. Just 17% of the respondents rank cost as the most important consideration.

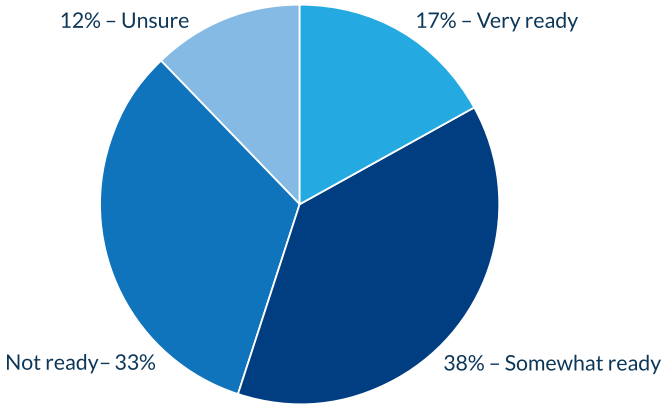
Biggest Challenge When Implementing a Solution



Security concerns limit use of cloud

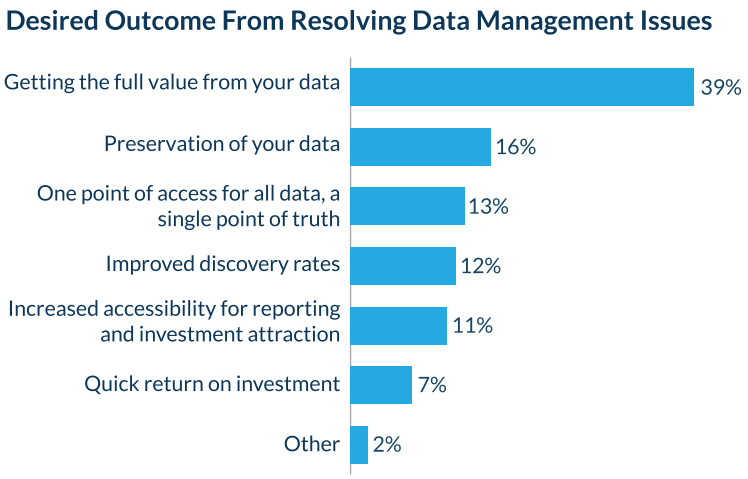
Even though more than half of respondents feel they are "very " or "somewhat" ready to leverage the cloud for geoscience data management and access – and many already are - a full 32% consider security the cloud's biggest drawback. Cost, performance and reliability are also concerns, but keeping data secure is by far the most common challenge. The exceptions are those working in the education sector or who identified as data administrators. They are more worried about cost.

Readiness to Leverage the Cloud



Getting full value tops the wish list

About 40% of the respondents feel that the most significant outcome from resolving data management issues would be to get full value from their data. Next on the wish list are preserving data, having one point of access for all data, increasing discovery rates, and improving accessibility for reporting and attracting investment. Geosoft broadened the outcomes question in 2017 to include more options based on feedback from previous surveys.



Conclusions

Accessibility and security concerns are holding organizations back from getting the full value of their data. To save time and increase efficiency, they need to a single search tool. To properly leverage the computing power of the cloud, they need better security.

Most respondents would prefer to purchase a commercial solution to outsourcing or developing a solution in-house. While cost remains a significant barrier, limited resources for due diligence or a poor culture for managing data are also preventing organizations from selecting and implementing geoscience data management solutions.

More information is available in the survey report which can be downloaded from the Geosoft website.

Tuesday 20 February 2018

0830–1010
TUESDAY 20 FEBRUARY 2018

4A PNG AND NZ

INNOVATIVE EXPLORATION IN PAPUA NEW GUINEA; PAST, PRESENT AND FUTURE

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Two of the recent, global gas discoveries and field extensions, Pnyang and Muruk, were in the mountainous jungle of PNG requiring innovative exploration techniques. Prior to the 1970s, PNG prospects were defined by field mapping and drilled where there was river access. Regional gravity data, refraction data and heli-supported rigs led to the drilling of wells in the Highlands in the 70s, including using slim-hole rigs, leading to major oil and gas discoveries in the 80s. These targets were almost all defined by detailed structural modelling of outcrop data as the few seismic reflection lines were of limited value. During the 90s many new techniques were tried, including passive seismic, magneto-tellurics, aeromagnetics, fission track analysis and Sr isoptope dating of the Miocene limestones, as well as improved, but expensive, seismic acquisition. The modern era of enhanced exploration has been facilitated by access to high-resolution 3D digital data, particularly topographic data that has allowed meaningful static corrections to gravity, magnetics, EM and 2D seismic data as well as the construction of detailed 3D structural models. In the future it is unlikely that reflection seismic data will significantly improve, but the order of magnitude improvements in gravity gradiometry combined with topography defined by LIDAR will make it a significant 3D exploration tool. 3D Finite element mechanical modelling of structures will become routine, constrained by new dating techniques such as limestone thermochronometry. This will facilitate 3D basin modelling and much improved exploration efficiency, likely to lead to a new wave of discoveries. The easy plays have been found. The hard plays are now increasingly detectable.

4D CHARACTERISATION OF PNG'S PETROLEUM SYSTEMS

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Mesozoic and Tertiary clastic and carbonate reservoirs are prolific producers of high quality liquid-rich gas. Onshore PNG. LNG projects are among the lowest cost and most profitable globally. Accordingly there has been a recent resurgence of petroleum exploration in PNG.

In 2015 Oil Search undertook a country-wide petroleum Common Risk Segment analysis that highlighted potential for giant new oil and gas fields of sufficient scale to support future LNG projects. It also concluded that 40 trillion cubic feet of gas plus 550 million barrels of oil resources remain to be found (representing approximately 60% of PNG's total petroleum resource).

In 2016 Oil Search completed an ambitious integrated structural, stratigraphic, burial, maturation, migration, uplift and erosion model of PNG's total petroleum system to quantify the locations for highly prospective under-explored regions.

Tectonic events at plate and basin scales were re-assessed and correlated within a new country-wide PNG chrono-stratigraphy of regionally mappable sequences and flooding events, some of global extent.

A base Tertiary mega-sequence boundary is mappable over the entire onshore to deepwater regions. 130 1D burial models combined with restored 2D structural and stratigraphic cross sections, have contributed to a new regional petroleum charge model of the foldbelts, foreland and offshore regions.

It is concluded that petroleum was generated pre-foldbelt during Late Cretaceous times in interior PNG, while petroleum is currently being generated at the present day mountain front.

A holistic 4D charge model explains why very young foldbelt traps are petroleum charged.

STRUCTURAL AND RESERVOIR DEVELOPMENT OF THE WESTERN PAPUAN BASIN GAS AND CONDENSATE FIELDS

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The Stanley, Elevala, Ketu and Ubuntu gas-condensate fields are located within the foreland of the Western Papuan Basin, PNG. Interpretation of 2D seismic across the basin has revealed the importance of basement architecture and the regional Northwest trending 3KB fault system for trap and reservoir development.

The Miocene/Pliocene compression, responsible for the thrust structures of the Papuan Foldbelt, had a relatively minor topological impact in the foreland. However, trap development within the Western Papuan Basin was influenced by this compression through inversion of pre-existing faults and enhancement of compactional drape of reservoirs over pre-existing basement highs.

Economically viable reservoirs (Elevala, Toro and Kimu Sandstones) have been intersected by several exploration and appraisal wells in the Western Papuan Basin. The Kimu and Elevala Sandstones are absent in the main producing fields of PNG, consequently very little is known about the depositional controls of these reservoirs. A detailed reservoir characterisation study was required to underpin foreland resource development and evaluate potential hydrocarbon recovery. Geophysical reservoir characterisation techniques were of limited value due to the poor vertical resolution of the reservoir on the 2D seismic, therefore core data and sedimentary analogues were used to map the spatial distribution of reservoir sands and develop palaeogeographic models.

Horizon Oil's activities within the Western Papuan Basin have contributed to the understanding of the structural regime and reservoir development of the area, proved commercial resources

and highlighted numerous prospective structures. The purpose of this paper is to present these findings from a relatively under-reported region of PNG.

0830–1010
TUESDAY 20 FEBRUARY 2018

4B WEST AUSTRALIAN BASINS SYMPOSIUM

ONSHORE INVENTORY – TARGETING NEW BASINS (OFFICER, PERTH, CANNING BASINS)

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Following the 2016 publication of Volume 1 of the Onshore Basin Inventory, Geoscience Australia is continuing to provide a concise inventory of available data and current geological knowledge of onshore basins of Australia. In Volume 2, presented here, three new basins, the Canning, Officer and Perth basins expand on this work. These reports provide a comprehensive, whole of basin inventory of the geology, petroleum systems, exploration status and data coverage for these basins. They incorporate information gathered by the precompetitive work programs undertaken by Geoscience Australia and state and territory governments, as well as publically available exploration results and geoscience literature. This information, in conjunction with the eight previously released basins, will assist in advising the Australian Government, state and territory governments and other stakeholders, such as the petroleum industry, about the exploration status and potential hydrocarbon prospectivity of onshore Australian basins. Furthermore, this work provides an assessment of outstanding issues and unanswered geological questions, and provides recommendations for future work to address these.

LINEAR TRENDS OF PALEO-POCKMARKS AND FLUID FLOW PIPES IN THE JURASSIC AND TRIASSIC SEDIMENTS OF OFFSHORE NORTHWEST AUSTRALIA

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This study records 319 paleo-pockmarks with associated focused fluid flow pipes within the Jurassic and Triassic sediments over three study areas on the Exmouth Plateau, offshore Northwest Australia. The paleo-pockmarks are identified along a surface that represents the top of the Jurassic sediments, while the fluid flow pipes extend into the Triassic sediments from the base of the pockmarks. The pockmarks and pipes form in linear trends that are parallel to and laterally offset from the tops of extensional faults that extend from the top of the Jurassic sediments into the Triassic sediments where they terminate. The bases of the fluid flow pipes are observed to intersect and terminate along the extensional faults within the Triassic sediments. The pockmarks and associated fluid flow pipes are interpreted to have formed by extensional faults intersecting an overpressured unit in the Triassic sediments. This caused a localised reduction of lithostatic pressure along the overpressured sequence at the intersection which then acted as a focal point for the fluids to migrate vertically. The source of the fluid overpressure could not be confirmed in this study. The Triassic sequence is a known hydrocarbon source and 1D modelling shows that at the time of the fluid flow and pockmark formation, the Triassic sediments were entering the hydrocarbon production window. However, no evidence of hydrocarbons associated with the pockmarks was observed. Our findings identify fluid migration pathways that are seal risks for hydrocarbon reservoirs, but could also potentially be fluid migration pathways that were previously untested.

THE EFFECT OF FLEXURAL ISOSTASY ON DELTA ARCHITECTURE: IMPLICATIONS FOR THE MUNGAROO FORMATION

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The fluvio-deltaic Triassic Mungaroo Formation, North West Shelf of Australia, hosts vast resources of hydrocarbons. However, the mechanisms that generated its 4–6 km monotonous infill architecture (colloquially known as layer cake stratigraphy) remain elusive. The vertical fluctuation between fluvial and shallow marine deposits indicates that accommodation was created simultaneously with deposition. This suggests that the stratigraphic style of the Mungaroo formation was significantly controlled by the isostatic compensation of the sediment load. To test this we use a basin and landscape dynamics model, BADLANDS, that combines fluvio-deltaic processes (erosion and sedimentation) with flexural isostasy. To drive our simulations we use dimensions, gradient, water discharge and sediment flux from seismic and scaling relationships extracted from the Mungaroo Formation and different lithospheric elastic thickness (Te) to account for the effect of dissimilar lithospheric rigidities and flexural isostasy. Results show an increase in delta size and decrease in sediment thickness as the lithospheric elastic thickness increases. These models help explain how thick deltaic sequences can be generated in a lithosphere with low Te values. This is in accordance with deep seismic data that shows lithospheric thinning underneath the Triassic Mungaroo delta. Future research will focus on comparing the synthetic stratigraphy extracted from the models with the stratigraphic record. This study provides a valuable quantitative approach for understanding how the isostatic compensation of the sediment load can control the architecture of fluvio-deltaic deposits, which has implications for reservoir modelling.

MESOZOIC TO CENOZOIC DEPOSITIONAL ENVIRONMENTS AND FLUID MIGRATION WITHIN THE CASWELL SUB-BASIN: KEY INSIGHTS FROM NEW INTERPRETATION AND MODELLING OF THE SCHILD PHASE 2 3D

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The offshore Browse Basin formed as a result of several phases of tectonic development occurring throughout the breakup of the

North West continental margin of Australia. The major basin forming events which consisted of cycles of extension, inversion and thermal subsidence occurred from the Permian through to the Late Cretaceous. The basin architecture is characterised by a series of north-east trending depocenters, including the south-eastern Yampi and Leveque shelves; the central Caswell and Barcoo sub-basins; and the outboard deep water Scott Plateau. The Schild II Broadband 3D survey is located approximately 170 km off the West coast of Australia within the Caswell sub-basin, which is a major central depocenter of the Browse Basin. The survey is in close proximity to the Icthys gas field and Cornea oil field, covering approximately 2460 km², in water depths ranging from approximately 200 to 300 m. New interpretation has been undertaken, including stratal slicing and attribute analysis to identify and delineate depositional features and potential hydrocarbon targets within the Schild 3D. In addition to mapping key target intervals, primarily the Jurassic Plover Formation, the interpretation of large structures at considerable depth provides new insights into the prospectivity of older Mesozoic and Paleozoic intervals. Of key relevance is the presence of deep structures that represent potential candidates for Permian events associated with glaciogenic deposition. Structures potentially associated with salt mobilisation have also been inferred from pre-existing seismic interpretation in the area.

0830–1010
TUESDAY 20 FEBRUARY 2018

4C NON CONVENTIONAL

INTEGRATED SEISMIC (IS) FOR SHALE GAS EXPLORATION AND MANAGEMENT

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Seismic integration has been a successful accessory in every data interpretation project. For shale gas exploration design, development and implementation, high-resolution seismic data are necessitated. In this context, every exploration project needs multi-disciplinary datasets and their integration that can minimise the ambiguity of the interpretative outcomes. What are integrated solutions for imaging and interpreting shale gas and how do they impact our shale prospect business? How do we organise and standardise our integrated workflows to address issues of exploration, field development, including drilling campaigns of the unconventional reservoirs? So far, the conventional reservoirs of many worldwide basins did produce even without integrated workflows. With the increase in intricacy in structural and stratigraphic settings, in particular with the fractured shale environments, exploration and field development plans have become multifaceted, complicating the field operations. How do we take on the exploration, development and drilling campaign decisions using the integrated seismic solutions? How do we suggest the 'integrated seismic' to our valued operators and service providers? Why are the conventional technologies failures and setbacks? How can we guide and recommend the petroleum companies on appropriate technologies and the reserve computations in shale gas environments? We come up with an 'Integrated Seismic' (IS) strategy, addressing these issues and challenges. The applicability and feasibility of IS in various exploration projects including their execution and implementation in worldwide shale gas basins are discussed. IS has been playing a vital role, making huge impacts on the integrated interpretation projects, especially during prospect identification and risk evaluation stages.

USING MULTIAZIMUTH SEISMIC DATA FOR ANISOTROPY ESTIMATION IN AN UNCONVENTIONAL RESERVOIR

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There are various static and dynamic reservoir characteristics that control the prospectivity and productivity of wells in an unconventional reservoir. Many of these characteristics have proxies among pre and post stack attributes that can be derived from Multiazimuth Seismic data. Amplitude and velocity variation with azimuth can be used to predict fracture strike and relative fracture density and define potential structural sweet spots. P-wave velocity and amplitude information from a Multiazimuth 3D seismic data (calibrated to wells) has been used in the Nappamerri trough, Cooper Basin to estimate fracture intensity and orientation. Stress maps were generated to identify areas of higher anisotropy and areas of lower minimum horizontal stress. The use of P-waves to detect azimuthal anisotropy represents a significant cost benefit when compared to the traditional use of shear waves for this purpose. Application of this technique provides a lower cost seismic tool (when compared to 3D multicomponent seismic), to identify reservoir 'sweet spots' and is anticipated to improve drilling results.

A NEW COMPUTATIONAL MODEL TO PREDICT BREAKDOWN PRESSURES IN CASED AND PERFORATED WELLS IN UNCONVENTIONAL RESERVOIRS

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Unconventional shale reservoirs are characterised by their extreme low permeabilities and their high *in situ* stresses. Multi-stage hydraulic fracturing therefore plays a key role in developing such reservoirs. However, depending on the *in situ* stress magnitude and/or regime, breakdown pressures can be too extreme to achieve, given the available surface horsepower capabilities. The local principal stresses surrounding perforation tunnels dictate the required breakdown pressure to induce enough stress to exceed the rock tensile strength.

This paper presents a newly developed model to predict the breakdown pressures in cased and perforated wells. Given an arbitrary azimuth and inclination of the wellbore and the *in situ* stress magnitude/regime, the model calculates the local stresses around the perforations and consequently predicts the perforations' breakdown pressure and the initial fracture plane orientation.

The results from the model indicate as to which perforation initiates first, creating a mini-fracture that extends to create a dominant fracture. This dominant fracture would be the only fracture extending, due to the induced stress shadowing on other mini-fractures and increasing the respective in-situ principal stresses. The model also aids cluster and well placement for highly deviated wells to better identify sweet spots where breakdown pressures are minimal, resulting in maximum hydrocarbon accumulations possible. If the perforations clusters are placed in zones with extreme local principal stresses, the near wellbore fracture widths would be too small to admit any proppant, leading to early proppant screenout. The results from the model shows a critical perforation phasing angle that should be avoided, as the local principal stresses maximise, increasing breakdown pressures. The model aims to advance the current understanding of fracture initiation in highly deviated wells in shale reservoirs. It can also assist engineers to better select sweet spots for well and cluster placement to avoid excessive breakdown pressures and/or potential early proppant screenout.

AN OPTIMISED HYDRAULIC FRACTURING TREATMENT ON CHALLENGING RIZQ FIELD

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Hydrocarbon production from unconventional reservoirs is often associated with hydraulic fracturing operations. In many cases however, the high *in situ* stresses and complex natural fracture network hinder an effective stimulation process. Therefore, different strategies are adopted to increase the success chance of stimulation. These strategies are in many cases field dependent and thus cannot be extended to other fields. In this study we demonstrate a new work flow introduced to ensure a successful stimulation process in an unconventional gas field in Pakistan. Well Rizq-01 was drilled as an exploration into challenging PAB formation which is tight sandstone with 0.3 mD permeability but highly fractured. Exploration wells in offset fields were drilled and stimulated in the same formation and resulted in screening-out and inability to place enough proppant due to fracture complexity and high in-situ-stresses. To overcome these challenges, extensive petrophysical and geomechanical analysis were performed to introduce a new workflow for stimulation.

The workflow includes:

- Extracting the intensive well log information for better understanding of stress barriers, stress magnitude and orientation, Young's Modulus, formation fluid information, etc.
- Sensitivity analysis on the hydraulic fracturing Treatment including the proppant size, type and volume, and fluid system. The design was based upon geomechanical and petrophysical interpretations of the openhole log data.
- Redesigning the fracturing treatment process utilising a first-of-its-kind onsite pre-frac test results, providing it helpful in the absence of bottomhole gauge.

The study therefore summarises the challenges, the work flow implemented, and the lesson learnt for successful stimulation job in Rizq Field.

0830–1010
TUESDAY 20 FEBRUARY 2018

4D GEOPHYSICS TECHNOLOGY

MATHEMATICAL PROPERTIES AND PHYSICAL MEANING OF THE GRAVITY GRADIENT TENSOR EIGENVALUES

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The eigenvalues of the gravity gradient tensor can be expressed as functions of two parameters: a magnitude and a phase. The decomposition gives physical meaning to the eigenvalues: the magnitude measures the amount of curvature and the phase is related to the type of source. A modified phase eigenvalue offers the interpreter an enhanced version of the vertical gravity gradient which is demonstrated with model data and applied to FALCON airborne gravity gradiometer data from the Perth Basin, Australia.

APPLICATION OF FREQUENCY DOMAIN INDUCTION EM SOUNDINGS WITH CONTROLLED SOURCE (FDEMS METHOD) FOR PRECISE TRACING OF BOUNDARIES IN GEOELECTRICAL SECTIONS

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The FDEMS method was introduced in the former USSR at the turn of the 50s and 60s of the last century as an integral part of the triad of induction EM methods (MT, FDEMS, TDEM), which were actively developed in the 50s after the grand discoveries by A. N. Tikhonov and L. Cagniard. The method was not widely used, primarily due to lack of suitable hardware and software for data processing and interpretation. Nevertheless, FDEMS was actively developed in certain regions of Russia and Ukraine until the present day. Interest in the method is supported by the potentially high accuracy of mapping high-resistivity boundaries, since in the FDEMS method there is a direct relationship between the ratio (R/H) of the sounding spacing (R) to the depth (H) to the high-resistivity reference horizon pronounced by significant points of amplitude and phase frequency characteristics (curves). A number of successful FDEMS surveys were completed on the Ukrainian Shield and its slopes, Dnipro-Donetsk basin (Ukraine) and different parts of Russia and Uzbekistan that achieved positive results (1977–2000). To date, the capabilities of modern multifunction and multichannel equipment and software for processing and interpreting field data allows to realise to a large extent the prospective capabilities of the FDEMS method for high-precision mapping of boundaries in the geoelectric section and mapping of low-contrast objects.

APPLICATION OF PASSIVE SEISMIC IN DETERMINING OVERBURDEN THICKNESS: NORTH WEST ZAMBIA

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There are several ways to estimate the overburden cover thickness. One of the non-invasive and inexpensive ways to rapidly estimate the cover thickness is the Horizontal-to-Vertical Spectral Ratio (HVSR) of the ambient seismic noise method. This approach utilises a broadband three-component sensitive seismometer to record ambient noise (or microtremor) induced by the wind, ocean waves and several anthropogenic activities. These microtremors are mainly composed of Rayleigh Waves propagate in the surface layer.

Tromino, which works on HVSR principle, is a very light and portable instrument that records seismic noise in the frequency range of 0.1 to 1024 Hz and capable of estimating overburden cover greater than 80 meters depending on the ambient noise strength and geological setting of the area.

The average ratio of the horizontal-to-vertical (H/V) component of the shear wave (Vs) spectrum is used to calculate the resonance frequency at a particular station, which is used in inferring the overburden thickness using one or more existing drillholes in the area or local geological knowledge about the overburden. This paper discusses different methods to calculate the overburden thickness, which includes calculation using regression equation or hybrid approach.

This paper shows the results of a Tromino survey in North West Zambia and comparison of estimated overburden thickness using different methods. The results were further compared with those determined from Audio-magnetotellurics and drilling data. Tromino successfully estimated the overburden thickness and mapped the bedrock topography with reasonable accuracy.

SCINTILLATORS FOR SPECTRAL GAMMA-GAMMA AND PGNAA IN MINERAL EXPLORATION

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Current gamma-ray detectors, based upon scintillation, are not likely to perform well in narrow diameter logging-while-drilling (LWD), such as NQ diamond drilling. The normally used scintillators of NaI, CsI and BGO materials, are not sufficiently dense to properly represent the gamma ray spectrum. Also, their resolution is not high enough to compensate for lack of stopping power in PGNAA applications. In the case of BGO it performs so poorly with respect to resolution and temperature sensitivity that the higher density does not compensate fully.

We have evaluated several novel halide and oxide scintillators that might improve the viability of spectral Gamma-Gamma and PGNAA in small diameter LWD. Specifically, we have looked at GAGG, YAP, SrI, CWO and ZWO scintillators and found that GAGG and CWO are good for spectral Gamma-Gamma use and that YAP and SrI may be a useful alternative to LaBr in PGNAA applications. However, we believe that very dense scintillators such as LGSO with moderate resolution capability are even better for measuring line spectra from PGNAA with small, less than 40 mm diameter, scintillator detectors.

0830–1010
TUESDAY 20 FEBRUARY 2018

4E STRATEGIC AND INDUSTRIAL

STRATEGIC AND INDUSTRIAL MINERALS LEADING THE NEXT PRODUCTION REVOLUTION

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The last decade of rapid industrialisation and urbanisation particularly in China led to a rapid growth of minerals particularly those required for infrastructure and construction.

The next decade will be equally dramatic but the growth will shift to the minerals required for the next production revolution including renewable energy, energy storage and energy reduction.

Minerals containing materials such as lithium, vanadium, graphite and cobalt are used in batteries and demand is estimated to grow at 14% CAGR. Other minerals such as rare earths, high purity alumina and high purity quartz are also expected to be in high demand.

The expected growth in electric vehicles will encourage changes in the production and demand of traditional materials such as steel and glass as well as changing demand for metals such as copper and aluminium.

Understanding these changing market forces and the changing demand for minerals is essential to determine where future exploration and capital investment will be most effective.

THE PILGANGOORA LITHIUM-TANTALUM DEPOSIT – GEOLOGICAL OVERVIEW AND EVOLUTION OF DISCOVERY

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The Pilgangoora Lithium-tantalum pegmatite deposit with a total resource of 156.3 Mt grading 1.25% Li_2O and 128 ppm Ta_2O_5, is a globally significant hard-rock lithium-tantalum deposit. The deposit is located in the East Pilbara Terrane of the northwest Pilbara Craton in Western Australia. The Northwest Pilbara Craton is one of the world's major lithium-tanatlum provinces with large scale lithium-caesium-tantlum bearing pegmatites located at Mt Francisco, Wodgina, Pilgangoora and Strelley.

Pegmatites bearing columbite-tantalite at Mt. York were first described in government geological surveys in 1906. Subsequent interest in the pegmatites focussed on their tin and tantalum mineral potential, with small scale hardrock, eluvial and alluvial mining, chiefly in the period 1947–1978. Larger scale alluvial and eluvial mining of tin-tantalum was carried out over 1978–1982 and 1992–1996 by a number of junior companies. In May 2014, Pilbara Minerals acquired the Pilgangoora Project for its lithium potential and has since drilled over 1450 holes for approximately 120 000 metres.

The Pilgangoora pegmatite intrusions crop out in a well exposed greenstone belt, with little weathering at surface. Exploration drilling programs along with detailed geological mapping of the Pilgangoora tenement group has provided a better understanding of the geological setting of the fractionated pegmatite intrusions within the East Strelley greenstone belt. This work has led to the recognition of some valuable exploration criteria that may be applied locally to locate additional resources and, longer term, may be used more strategically to review other pegmatite fields across the Pilbara region.

EVALUATING RARE EARTH DEPOSITS

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There has been a significant growth in exploration activity for rare earth element (REE) deposits since the firming of prices began in 2003. Numerous deposits have been subject to detailed evaluation, though during this period only one new operation at Mt Weld, Western Australia is in production. One older operation at Mountain Pass, USA, re-opened in 2012 but, due to low rare earth prices, shut down in 2015. Chinese production dominates the world rare earth industry, accounting for approximately 85% of the world's annual production of ~110 000 tonnes, from numerous deposits in five provinces. It is reported that approximately 45 000 tonnes of Chinese production is illegal.

The talk will discuss a number of types of rare earth deposits including those hosted by carbonatite, alkali- intrusives and supergene material including heavy rare earth enriched examples. One important case-study will be discussed. The Mt Weld deposit, in Western Australia, was put into production after a 30 year exploration history and was only successfully drilled after 1991 once the regolith that hosts the mineralisation had been de-watered. This enabled the recovery of samples that had not suffered from the loss of fines. Its first reported resource estimates in 2002 achieved close reconciliations within a few percent of actual mined material.

In general, cut-off grades used to report resources for many REE deposits are unrealistically low and significantly less than those used by the only two recent Western operations. These cut-offs result from attaching notional values on the basis of available metal prices and unrealistically low costs associated with production and sales.

0830–1010
TUESDAY 20 FEBRUARY 2018

4F MAGNETOTELLURICS

PARTICULARITIES OF 5-COMPONENT MAGNETOTELLURIC SOUNDINGS APPLICATION FOR MINERAL EXPLORATION

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In the application of electroprospecting for mineral exploration, there are few clearly observed trends based on the development of electroprospecting technologies. These are hardware, software and computer technologies aimed at: (a) the increase of electroprospecting application in comparison with other EM methods; (b) application of electroprospecting at all stages of the exploration cycle; (c) the increase of application of induction electroprospecting methods. These technologies are based on the study of the natural EM field of the Earth (NEMFE). A special role here is played by the method of Broadband Magnetovariational Profiling (BMVP).

Three stages in the application of electroprospecting are quite clearly distinguished: (a) exploration for new mining provinces according to the distribution of resistivity in the Earth's crust and upper mantle (the AusLAMP project, a revolutionary idea proposed by Australian scientists; deep MT, scale 1 : 5 000 000 – 1 : 1 000 000); (b) exploration for large conductive ore bodies, areas with a prospecting survey square area of more than 100 km^2 by airborne geophysics, for areas with smaller size – 5-component AMT on a scale of 1 : 200 000 – 1 : 50 000; (c) detailisation and support of drilling operations, mapping of veins and dikes – 5-component AMT on the scale 1 : 20 000 – 1 : 5000 in complex areas with induction and geometric soundings using control source if Induced Polarisation is an exploration factor.

SFERIC SIGNALS FOR LIGHTNING SOURCED ELECTROMAGNETIC SURVEYS

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Lightning strikes generate electromagnetic (EM) waves, known as sferics, which are used in passive Audio-Frequency Magnetotelluric (AMT) and Geomagnetic depth soundings (GDS). Global lightning networks detect sferics and catalogue the time and location of up to four million lightning strikes per day. In this research, we use lightning network data to predict time of arrival, azimuth, and amplitude for each known sferic in our time series EM data.

A significant and ill-posed problem in conventional AMT surveys is the identification and removal of galvanic distortion. Since conductors effectively rotate electromagnetic fields, we infer the location and geometry of local and regional structures by calculating the rotation of measured data from their predicted

arrival azimuths. To demonstrate our approach, we carried out a Global Positioning System (GPS) synchronised AMT survey along a profile over a known mineral deposit in Western Australia, using a local AMT reference site to estimate electromagnetic field gradients along the survey profile. Assuming that the roving and reference sensors observe the same primary field, then the gradient operator effectively removes primary fields leaving only secondary fields generated by subsurface conductors. We used lightning network data to correct our reference data for local distortions, and then calculated profiles of the magnetic field gradient over the known conductor. Forward modelling of Fixed Loop Electromagnetic (FLEM) data corroborates our GDS results.

0830–1010
TUESDAY 20 FEBRUARY 2018

4G REGIONAL MAPPING

NATIONAL MINERAL EXPLORATION STRATEGY: A VISION FOR UNLOCKING AUSTRALIA'S HIDDEN MINERAL WEALTH

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The National Mineral Exploration Strategy sets out a 5-year program to overcome major challenges to discovery of new mineral deposits in frontier terrains across Australia. The Strategy, as endorsed by the COAG Energy Council, will be driven by the Geoscience Working Group (GWG), comprised of the Commonwealth, State and Territory government geological surveys. The Strategy will be delivered in partnership with the resources industry, the research community, and the services sector. It includes programs to attract increased investment into the Australian exploration sector but does not address the financial or regulatory challenges facing mineral exploration.

The Geoscience Working Group (GWG) will deliver the Strategy by:

(1) Encouraging investment through a renewed commitment to the creation and delivery of government-funded pre-competitive geoscience, and a refreshed approach to the global promotion of Australia.
(2) Harnessing our capability through a cross-institutional research venture focused on delivering the applied geoscience needed for industry to better explore beneath the covered regions of Australia, as well as continued development and promotion of Australia's world-leading METS sector.
(3) Protecting the environment through provision of robust baseline pre-competitive geoscience data for evidence-based decision making and reducing the exploration footprint.
(4) Supporting our people and communities through wider engagement and clear communication of relevant geoscience information, and the economic and social benefits of a vibrant minerals industry to a broad audience.

This paper will outline each of the four themes with examples from across Australia of the actions currently underway.

AN INTEGRATED APPROACH TO MAPPING CRUSTAL GEOLOGY AND STRUCTURES IN THE NE CAPRICORN OROGEN, WESTERN AUSTRALIA: IMPLICATIONS FOR URANIUM EXPLORATION

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Crustal-scale geology and structures in the NE Capricorn Orogen have been mapped using techniques from various disciplines. Several interpretations were generated from the processed gravity and magnetic data. The interpretations were tested by petrophysical constrainted gravity and magnetic forward modelling and ground truthed by field mapping, core logging and structural analysis. The significance of the structures at surface was tested by logging and mapping the Paleoproterozoic Bresnahan Basin for sedimentary facies changes across faults. Additionally, a nearby seismic line was used to further constrain the interpretations.

The integrated approach to mapping indicates more prospective locations for uranium exploration. While uranium occurrences are common across the region, the significant deposits are associated with interpreted major structures. The absence of major crustal-scale structures in the NE of the study area is a likely reason for the lack of major uranium deposits in that region. The work indicates that hanging wall blocks associated with faults bounding a major longitudinal sub-basin of the Paleoproterozoic Ashburton Basin offer better potential for larger uranium deposits. The hanging wall block is unconformably overlain by the Bresnahan Basin where the geology adjacent to the sub-basin bounding faults appear to be 'bleached' with clay replacement of detrital feldspar from the rock. This along with common carbonate veins maybe indicating a distal alteration halo of unconformity type uranium deposits.

ARCHEAN CONTROLS ON BASIN DEVELOPMENT AND MINERALISATION IN THE SOUTHERN CAPRICORN OROGEN

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Basins along the northern margin of the Yilgarn Craton developed in response to extensional and compressional processes in the Paleoproterozoic along the craton margin. Early extension resulted in the formation of the Yerrida Basin as a large single basin over the northern Yilgarn Craton. Subsequent rifting led to voluminous volcanism in the northern part of the 2.2 to 1.9 Ga Yerrida Basin, within two depositional centres – the c. 2.03 to 1.96 Ga Bryah and Mooloogool Sub-basins. Yilgarn Craton crust can be mapped using gravity and magnetic data beneath the Yerrida Basin, and Mooloogool Sub-basin. However, it can't be mapped below the Bryah Basin, implying the formation of an ocean in this region. The degree of rifting of the Yilgarn Craton, and resulting architecture influenced subsequent basin development, and deformation in the region. For example, in areas where Yilgarn Craton crust can't be mapped beneath basin sediments deformation is pronounced with the formation of disharmonic folds, refolded folds, and

anastomosing shear zones. The southern part of the Yerrida Basin and the Earaheedy Basin formed shallow depositional centres over the Yilgarn Craton, and subsequent deformation in these regions is less intense. Base metal mineralisation in the region can, in part, be related to the presence of deep crustal scale structures that initially developed in the Archean, and were re-activated during the Proterozoic. However, the location of c. 1800 Ma orogenic Au mineralisation in the Bryah Sub-basin may not have been influenced by deep crustal-scale faults that initially formed during the Archean.

0830–1010
TUESDAY 20 FEBRUARY 2018

4H GROUNDWATER CASE STUDIES

CHARACTERISING THE SPIRITWOOD VALLEY AQUIFER, NORTH DAKOTA, USING HELICOPTER TIME-DOMAIN EM

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Buried valley aquifers, consisting of permeable sand and gravel deposits in eroded bedrock valleys, are important sources of groundwater supply in many regions of the United States and Canada.

Investigations of the Spiritwood aquifer in southern Manitoba by the Geological Survey of Canada and other workers, have demonstrated the value of helicopter time domain electromagnetic (TDEM) surveys in aquifer mapping and characterisation using the contrasts between Quaternary glacio-lacustrine sand-gravels (high resistivity) that are relatively permeable and clay-tills (low resistivity) that are relatively impermeable, as well as the deeper, much less resistive Cretaceous Pierre Formation Shale basement rocks. This success provided the impetus for the North Dakota State Water Commission to fly a VTEM helicopter EM survey in the Jamestown, ND region in October, 2016.

The VTEM data collected over the Spiritwood-JT block allowed for geological mapping from near surface to depth, in spite of relatively weak resistivity contrasts (<10X). These data were inverted with a layered-earth algorithm to produce resistivity-depth models. These models were able to resolve the location and depths to the top and bottom of the Spiritwood aquifer throughout the central portion of the block providing more detailed pictures of the aquifer's geometry. In addition to resolving the main aquifer as well as its deeper channels, the VTEM data and models highlighted several smaller, previously undiscovered aquifers that cross-cut/branch-off from the main Spiritwood channel. These are interpreted as probable transverse low-K barriers that were apparent from the existing test drilling and aquifer testing.

REINTERPRETATION OF WIRELINE LOG DATA IN THE EASTERN GALILEE BASIN, QUEENSLAND: STRATIGRAPHICAL AND HYDROGEOLOGICAL IMPLICATIONS

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In response to the Millennium drought and increased demand for water throughout Australia, the Bureau of Meteorology (BoM) was given the role of compiling and delivering Australia's water information under the conditions set out in the Federal Water Act 2007.

To achieve this the BoM developed the Australian Water Resource Information System (AWRIS) and the National Groundwater Information System (NGIS) to support AWRIS. Functionality of the NGIS relied on compiling state and territory groundwater databases and the completeness of data in these databases was critical in facilitating data migration. Groundwater bores in the Galilee Basin were identified as a priority target for addressing data gaps.

A stratigraphic framework was created using published wireline log interpretations to map structure surfaces for the Galilee Basin. Assessment of these structure surfaces and wireline log interpretations identified numerous inconsistencies with the established basin stratigraphy. This is partially attributed to the large number of interpretation sources, exploration relevance and an incomplete understanding of facies variability.

Systematic reinterpretation of the published wireline log data was undertaken to validate and reassign inconsistent interpretations in the eastern Galilee Basin. Reinterpretation has resulted in shifting formation top picks vertically by up to 300 m in some instances, leading to significant modification of some structure contour surfaces.

Uncertainty over the internal architecture of the Galilee Basin has significant implications for understanding the hydrogeology of aquifer systems and springs in the basin. Reinterpretation by a single operator has assisted in removing some of this uncertainty and provided a consistent dataset of interpretations.

1040–1220
TUESDAY 20 FEBRUARY 2018

5A PNG AND NZ

PLIO-PLEISTOCENE RIVER DRAINAGE EVOLUTION IN NEW GUINEA

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The drainage of New Guinea has evolved rapidly since Pliocene time. Relief growth initiated in accreted oceanic terranes in the north and immigrated into the Australian margin interior over time. The present-day drainage retains inherited elements of an ancient fluvial system that routed sediments from these northern terranes through the Central Highlands into foreland flexural basins, epicontinental seas, and deep oceanic basins. The rise of the Highlands and of the Papuan Peninsula spurred drainage reorganisation, such that today little of the oceanic terranes still drains through the mountain range. This evolution has strongly affected the composition of the clastic sediments delivered to the shelves.

The topography retains the memory of some of the most recent changes. Most of the relief of the Papuan Peninsula formed during the past 5 Ma, driven by tectonic removal of the load of the peninsular ophiolites, accompanied by contractional collapse along the Aure-Pocklington trough. In the eastern Central Highlands, rapid drainage reversal results from flexural back-tilting under the load of the colliding Huon-Finisterre Range. Northward reversal is also observed at the western end of the Highlands. In the south, the Fly platform has experienced recent, widespread, non-tectonic and non-flexural uplift of deep origin that will ultimately close the Torres Strait.

The Quaternary drainage evolution will be used to calibrate the *Badlands* software developed by the Basin Genesis Hub, as a first step for simulating the evolution of topography and sediment delivery to the Australian shelf and Gulf of Papua in earlier times.

GEOPHYSICAL AND GEOLOGICAL CHARACTERISATION OF DREDGE LOCATIONS FROM RV SOUTHERN SURVEYOR VOYAGE SS2012_V06 (ECOSATI): HOTSPOT ACTIVITY IN NORTHERN ZEALANDIA

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In October–November 2012, a geophysical mapping and dredging campaign in the eastern Coral Sea was conducted on the *RV Southern Surveyor* during voyage ss2012_v06 (ECOSAT). Part of this campaign was focussed in northernmost Zealandia where volcanic seamounts and uplifted portions of the Lord Howe Rise were targetted to determine the age and extent of the Lord Howe Seamount Chain (LHSC) and to recover continental basement from the Lord Howe Rise. Our geophysical and geological analysis of dredge sites from the South Rennell Trough and Chesterfield Plateau confirm the extension of the LHSC ~300 km northward than previously identified, with an age-progression extending to ~27–28 Ma. These new samples, together with previously published results from the southernmost chain, show consistency with both Indo-Atlantic and Pacific hotspot models and further highlight the change in Australian absolute motion between 27–23 Ma. The recovery of trachytes at the Le Noroit seamounts (northern New Caledonia Trough) and aphyric lava, porphyritic lava and volcaniclastic sandstone along Nerus Reef and Landsdowne Bank provide some of the only indications of continental basement from northern Zealandia. Swath bathymetry analysis of dredge locations reveals consistently large discrepancies (in the order of 1000 m) with global compilations, and together with an analysis of gravity signatures, suggests complex basement structure in the area. The results of our sampling from northern Zealandia will assist in understanding the thermal history of Northern Zealandia and will provide a geological framework for resource exploration in this frontier basin exploration area.

COMPRESSIONAL EVOLUTION OF THE PNG MARGIN FROM AN OROGENIC TRANSECT FROM JUHA TO THE SEPIK

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A crustal-scale, fully restored section across the PNG orogenic belt reveals the Oligocene to Recent compressional deformation of the margin. The northern end of the section comprises the Landslip Metamorphics, an accreted continental terrane, separated from the main part of the fold belt by the Jurassic April Ultramafics and Om Metamorphics, interleaved with Eocene volcanics, which together constitute an accretionary prism. Existing maps show that the suture is overlain by distal Miocene sediments indicating Oligocene docking and probable compression prior to Early Miocene subsidence. The latter is consistent with Early Miocene extension in PNG and the emplacement of metamorphic core complexes in the Sepik area, but is also related to dynamic topography causing subsidence of the whole northern margin of Australia. Neogene compression commenced around 12 Ma with ~70 km shortening in the Om

terrane and ~38 km shortening in the Fold Belt. Existing thermochronology data indicate shortening of ~12 mm/year from 12–4 Ma, but only 2.5 mm/year from 4–0 Ma, consistent with a change in structural style in the Fold Belt from thrust to more ductile, fold-dominated deformation. The model also requires substantial thickening of the continental crust beneath the Muller Ranges, here represented by 'basement' underthrusting. Gravity modelling indicates the presence of sedimentary graben up to 10 km deep beneath the fold belt, which were strongly inverted, such as beneath the Lavani Valley. A key issue is when this inversion occurred, in the Oligocene or Pliocene, as this has a significant influence on the timing of hydrocarbon generation and migration.

TECTONIC AND GEODYNAMIC EVOLUTION OF THE NORTHERN AUSTRALIAN MARGIN AND NEW GUINEA

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Rapid convergence between the Indo-Australian, Southeast Asian, and Pacific plates in the Cenozoic has resulted in a complex tectonic evolution of Australia's northern margin. A lack of available geologic data leads to large uncertainties, such as the timing of the Sepik collision with the New Guinea margin, currently constrained to sometime between 50 and 30 Ma. Previous work suggested a link between the Sepik collision and a voluminous fast seismic anomaly presently in the mantle beneath Lake Eyre. Following from previous work, this study uses coupled plate reconstruction and numerical geodynamic software to test 50 Ma and 30 Ma collision timings of the Sepik terrane, along with an upper extent back-arc basin, to further refine our understanding of the source and trajectory of the slab beneath Lake Eyre and address uncertainties in the plate reconstructions. The results of mantle flow models indicate that the ~50 Ma collision timing is more likely. In addition, dynamic topography results support previous suggestions that dynamic subsidence relating to the down-going Sepik slab has had a significant influence on the evolution of the Eyre Basin, with up to ~100 m of dynamic subsidence since ~20 Ma. However, further work is required to address numerical issues relating to rapid thermal diffusion, and to investigate reasonable trench retreat velocities for intermediate (~3000 km) subduction zone lengths. This work highlights the benefit of numerical modelling of transient plate-mantle processes and their effect on basin evolution on the interiors and margins of continents affected by subduction.

1040–1220
TUESDAY 20 FEBRUARY 2018

5B WEST AUSTRALIAN BASINS SYMPOSIUM

CANNING BASIN – PETROLEUM SYSTEMS ANALYSIS

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High resolution geochemical analysis of Canning Basin oils and condensates demonstrated a common and potentially regional source rock. Ungani field oils suggest they were all generated within the peak oil window from a similar high quality marine source rock, which is clastic and contains bacterial and marine algal matter deposited under anoxic to sub-oxic conditions. Low GOR's are likely the consequence of the source rock type with gas removal possibly by water washing.

Liquids from the Yulleroo field were derived from a similar source to the Ungani oils, with the addition of dry gas from a higher maturity and/or more gas prone source. These liquids were generated and expelled at slightly higher maturity than the Ungani oils, with the current lean gas condensate phase the result of the addition of dry gas combined with minimal water washing. The Ungani and Yulleroo liquids resemble the L4 family previously attributed by GA to a probable Carboniferous age source.

Map based burial history and maturity modelling was undertaken incorporating eleven 1D models using a source rock model derived from the liquid geochemistry with Type B from the Pepper and Corvi organofacies. Burial history modelling and maturity modelling at the top of the Laurel Lower Carbonate shows maturity for gas expulsion in the main trough and oil to light oil expulsion on the flanks of the basin. Maximum burial in the basin took place immediately prior to the Fitzroy Uplift, resulting in the main phase of oil generation and expulsion taking place around 200a.

THE UNGANI OIL FIELD, CANNING BASIN – EVALUATION OF A DOLOMITE RESERVOIR

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The Ungani field was discovered in 2011 within the Fitzroy Trough, with oil reservoired in early Carboniferous dolomites of the Lower Laurel Formation, previously only encountered on the basin edges. It has produced 792 000 barrels of oil to December 2017. Production rates, well interference and material balance analysis suggest the reservoir has significant porosity and multi Darcy permeability with initial well rates of 1500 bopd. Recent drilling, the installation of artificial lift, and facilities upgrades in

late 2017 should enable field oil production rates to reach 3000 bopd in 2018.

Seventy metres of continuous core through the reservoir was acquired at the Ungani Far West 1 well in 2015 and this has enabled new insights into the heterogeneous reservoir architecture and support for upgrades to resource estimates. 3D structural analysis of 140 micron resolution helical CT-scans by CSIRO is used to directly measure vuggy connected macro porosity over 30% (pu), interspaced by a tight matrix with non-connected macro porosities not greater than 2.5% (pu). These measurements were up-scaled to calibrate porosity estimates derived from neutron-density and sonic log data and demonstrates that the log data does not adequately resolve the productive zones and confirms a greater net contributing and connected pore space than estimates based on log data.

The heterogeneity and prolific nature of the uppermost part of the reservoir had not been previously recognised and this has been compounded by poor log data coverage around casing shoes. Re-analysis of ditch cuttings samples from Ungani-3 using Chemostrat ICP-OES-MS was instrumental in proposing additional drilling at Ungani 5 (December 2017) to successfully re-target the upper-most part of the reservoir.

Significant oil prospectivity is identified from modern 3D and 2D seismic near Ungani and along an under-explored 200km long depositional belt extending both west and east from the field. Exploration drilling of a number of large high impact prospects along this trend is planned through 2018.

DEPOSITIONAL, DIAGENETIC AND MINERALOGICAL CONTROLS ON POROSITY DEVELOPMENT IN UNGANI FIELD, CANNING BASIN

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In late 2015, a 75 m thick section of Early Carboniferous Laurel Formation was continuously cored in Ungani Far West 1, an appraisal well 3 km away from the main Ungani field on the southern flank of the Fitzroy Tough in the Canning Basin. One of the main objectives of this coring program was to better understand the pore systems, mineralogy, and diagenetic history of the reservoir to allow calibration and extrapolation of the petrophysical evaluation of the field. Petrography, stable isotope, XRF, hyperspectral logging, grain density and CT scan studies were conducted on the core.

The core consists of a 12 m overlying sealing shale and 63 m of vuggy, fractured and dolomitised reservoir. The reservoir is commonly bioclastic-rich but pervasive dolomitisation hindered recognition of earlier depositional features. Upper carbonate facies are interpreted as shallow to moderate depth marine ramp-type deposits. The lower carbonate facies is suggestive of shallow platform top settings with 'reefal' constructing organisms. Bio-mouldic, fracture, cavern and inter-crystalline porosity resulting from multistage brecciation, fracturing, dolomitisation and dissoulution events are all critical to reservoir development.

Based on hyperspectral logging and thin section petrography, the reservoir is deemed to predominantly dolomite with late phase cements comprising of quartz, calcite, gypsum, anhydrite, chalcedony and pyrite. Variable grain densities that correspond with porosity have been noted throughout the core. This is likely to be a result of diagenetic alteration or possibly even depositional environment (conclusion to be established).

LAUREL GAS PLAY, CANNING BASIN – RECENT STRATIGRAPHIC LEARNINGS

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Well, core and seismic data from the Lennard Shelf and Fitzroy Trough were integrated to produce a predictive sequence stratigraphic framework of the Laurel Formation consisting of Lower, Middle and Upper depositional sequences.

Significant encouragement for potentially commercial flow rates was achieved by the hydraulic stimulation of the Middle Laurel in the Eastern Gas Province (Valhalla North 1 and Asgard 1 wells) in late 2015 and in the Western Gas Province (Yulleroo) in 2010. The Laurel tight gas play extends over a 20 000 km2 area developed within a 2000 m thick succession of marine clastics and carbonates. Condensate rich wet gas associated with overpressure is encountered regionally within low porosity and permeability sands at depths below 2000 m. This was correlated across the basin from Yulleroo to the Meda Embayment and Northern Gas Province where a number of prospective plays were identified.

Upper Laurel shallow marine sandstones commonly possess good oil and gas shows and have potential for tight gas where overpressured. A prominent Middle Laurel lowstand prograding shelf slope wedge supported by the presence of conglomerates in updip wells suggest better clastic sediment supply and the potential for the development of conventional lowstand topset sandstone reservoirs in the Northern Province.

The Middle Laurel interval in the Northern Gas Province likely consists of a similar and potentially better tight gas reservoir than the interval stimulated in the Eastern Gas Province. Further drilling is required to confirm this and also to prove the viability of the tight gas play in the Northern Gas Province.

1040–1220
TUESDAY 20 FEBRUARY 2018

5C NON CONVENTIONAL

NEW METHOD FOR MONITORING STEAM INJECTION FOR EOR AND FINDINGS SOURCES OF GEOTHERMAL HEAT

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A database of over 10 000 wells with open hole logs, of which over 600 wells are dedicated surveillance wells with whole core, time lapse Carbon/Oxygen, Neutron, and Temperature data is being used for evaluating Adrok's deep penetrating radar system.

Kern River (California) is on its way to recovering 90% of its OOIP and surveillance is playing a significant role in achieving such a world class milestone. Future growth for develop of the field and surveillance technologies still exist as well. To that end, we are looking at the possibly of surface only acquisition for Chevron's surveillance needs.

Significant time and effort was spent on dielectric logging in the 1970s–80s by operators and service companies. Adrok's Atomic Dielectric Resonance (ADR) claims to interact with the subsurface in the same region of the electro-magnetic spectrum as di-electric logging, but from surface measurement. First Principles predicts a rise in dielectric constant as temperature rises. Fieldwork was conducted during 2014 to 2016. The surveys were divided up into two groups, one for training (full access to database) and one for blind testing (no access to database). Surprisingly, the blind tests could detect the presence or absence of a single zone steamchest by a rise in dielectric constant at the correct spacetime.

The body of the presentation will describe in greater detail the technology, field experiment and results to date for Chevron. Results from onshore geothermal heat exploration at a number of sites in New Zealand, Cornwall and Northeast England will also be presented.

A NEW SYSTEM FOR EFFICIENTLY ACQUIRING VERTICAL SEISMIC PROFILE SURVEYS

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Vertical seismic profiles (VSPs) utilise seismic sensors placed in a borehole to record vibrations transmitted by a source at surface. These surveys provide data that can be used both to calibrate surface seismic surveys, and provide geomechanical properties. Although undoubtedly valuable, acquiring VSPs can be cost prohibitive, both due to the equipment acquisition cost, and the time required to acquire the survey. VSP acquisition systems fall into two broad categories, those that transmit the analogue data up a cable to be digitised at the surface and those that digitise the data downhole before transmission to the surface. The former have limited maximum depths, typically around 300 m, and require cables with a considerable number of cores (at least six per tool) and are thus usually limited to one or two sondes (the acquisition time of a survey is roughly proportional to the number of tools deployed). Digital tools are usually rated to greater depths and support a greater number of sondes, but are typically much more expensive and require specialised wireline cables. In this paper we describe a new system for acquiring VSP data. Our system digitises the data within each sonde but stores the data in memory for downloading at the surface. The system requires only four-core wireline cable, two of which are used for powering and communicating QC information with the sonde electronics. This system has the additional advantages of having a high depth rating and a theoretically unlimited number of sondes making it highly efficient.

WHAT WE KNOW, WHAT WE DON'T KNOW, AND THINGS WE DO NOT KNOW WE DON'T KNOW ABOUT HYDRAULIC FRACTURING IN HIGH STRESS ENVIRONMENTS

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Hydraulic fracturing in many Australian Basins, particularly the Cooper Basin has been successful in higher permeability, structured conventional plays. However, adaptation of North American strategies to Australia's complex, and highly stressed unconventional areas has resulted in less than adequate performance to progress further investment into widespread development these resources. This presentation will explore the obvious differences between Australian and North American stress settings, and the problems manifested by those differences in hydraulic fracture containment and behaviour. Further, as more unconventional targets are attempted, complementary strategies need to be considered based on fundamental geomechanical principles, relative to these basinal environments. This presentation will explore several problems, emerging potential solutions, and areas of ongoing research with the purpose of aiding Australia to tap into a vast supply of potential unconventional resources, which are currently under-appraised.

THE ROLE OF DIAGNOSTIC FRACTURE INJECTION TESTING TO IMPROVE RESERVOIR EVALUATION AND STRESS CHARACTERISATION IN COMPRESSIVE STRESS REGIMES

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The diagnostic fracture injection test, commonly known as a DFIT, is frequently used in conventional and unconventional reservoirs (e.g. tight gas, shale gas, tight coals) to calibrate the hydraulic fracture treatment. In a normal stress regime, a single test can calibrate the in-situ stress profile and provide parameters such as reservoir pressure and transmissibility. However, in strike-slip regimes a single test cannot adequately derive strain values to develop an accurate stress profile as compared to multiple, precise, well-designed multi-DFIT program. Thus, if more consideration were given to the design process and

stepwise implementation, a more robust stress profile and definitive reservoir characterisation can result from implementation of DFITs in low permeability, unconventional gas reservoirs.

This presentation will define the workflow of a multi-DFIT program and the governing equations for stress profiling to allow practitioners to incorporate DFIT data with other available data to derive accurate geomechanical parameters. Further, a well defined program can provide insight for hydraulic fracturing modelling and key information regarding natural fracturing and transmissibility for reservoir modelling. For unconventional, non-normal, tectonically-stressed reservoirs this includes defining minimum and maximum horizontal strains as well as intermediate stress values acting on known natural fracturing azimuths. Overall, a comprehensive set of recommendations and references are made for the practical application of DFITs to illustrate the overall benefit for the well design processes.

1040–1220 TUESDAY 20 FEBRUARY 2018

5D GENERAL GEOLOGY

GEOPHYSICAL DETECTION OF THE HYDROTHERMAL ALTERATION FOOTPRINTS OF ORE DEPOSITS

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Exploring deep or under cover means no expectation of a direct ore deposit signature in exploration data. The deposit, however, is part of a mineralised system with alteration assemblages that may extend kilometres. Where the architecture of such systems is generally understood in terms of alteration domains—the deposit 'footprint'—exploration strategy can focus on the identification of such domains and, in the best cases, use their spatial relationships to vector towards the ore deposit.

Potential fields data with extensive coverage are common, and high-quality airborne magnetic data are nearly ubiquitous in modern mineral exploration. The use of geophysical data is appealing because, although it does not directly respond to rock chemistry, it provides the greatest and most uniform areal data coverage. In the age of deep and undercover exploration, direct recognition of footprint-scale hydrothermal alteration from geophysical data is the holy grail of geophysical interpretation.

The key to geophysical recognition of alteration at the ore system scale is the assumption, typically met in practice, that the primary control on physical property variation across the system is formational and structural, with hydrothermal alteration a contributing secondary effect. Specialised interpretation workflows can take advantage of this assumption to create physical property models composed of primary (formational and structural) and secondary (alteration) physical property signatures that are fully consistent with geophysical data and whatever level of geological data is available. The secondary physical property signatures are in many cases directly interpretable in terms of hydrothermal alteration domains.

CREATING A NEW FRONTIER IN DETECTION AND DATA INTEGRATION FOR EXPLORATION THROUGH COVER

Robert Hough

With the recent declines in greenfields exploration activity and discovery success in Australia, a new wave of technologies and data products are needed. Australia is an old continent with much of its remaining mineral endowment obscured by a thick cover of weathered rock, sediment and soil materials. This presents a critical challenge for mineral exploration now and into the future, as the industry currently lacks the fundamental data, scientific knowledge and technological tools needed to discover new, world-class ore deposits buried beneath this cover. UNCOVER, is a national vision in Australia for the future for mineral exploration geoscience research to tackle the geological barriers to more tier 1 discoveries.

UNCOVER as a national initiative, has the potential to position Australian exploration geoscience research for a shift in collaboration for technology development, one that tackles the exploration through *deep* cover challenge as one of major national importance. As we move into exploring the deeper cover regions of Australia, we need to determine detectable signatures of buried mineral systems and ore systems from a number of varied sample media and with different technologies. Arguably, the challenge posed by the depth of cover to find the mines of the future is going to be in the 100s of m, given current mining practices from the surface combined with the economic realities. Firstly though, we need to know the extent of that thickness of cover, its stratigraphy, lithogeochemistry and physical properties. Comprehensive data that will in turn aid in more effective processing and interpretation of the regional data-sets collected e.g. magnetics, and increase confidence in our geological models of the sub-surface. While the cover is a barrier it also presents an opportunity and detection through cover may lead to new resource discovery within the cover itself.

Our ability to detect an anomaly in exploration rests not in the direct detection itself but in being able to place the data point into a regional geological context. For example, research on the geochemistry of the Fortescue Group volcanics assessing burial metasomatism effects has been undertaken in the Capricorn distal footprints project so that we can position the industry to place perceived geochemical, geophysical and mineralogical anomalism from similar lithologies into a broader geological and indeed regional context.

Australian researchers have long played a globally leading role in developing new approaches and technologies to support the minerals industry in exploration, most often through collaboration involving multiple organisations and with close industry engagement. Co-operative research centres and Centres of Excellence are vehicles that have been very important in the focus and drive for innovation to support the industry to tackle technical challenges involved with mineral exploration in Australia. Recently, the SIEF, MRIWA, GSWA and industry supported Capricorn distal footprints project between CSIRO, UWA and Curtin University teams also reflects a highly collaborative approach to the challenge, including in a highly multi-disciplinary manner with a very strong cohort of early career researcehrs.

Acknowledgements: The presentation will include much content from my CSIRO colleagues and I thank each for their important contributions.

EPISODIC MINERALISING FLUID INJECTION THROUGH CHEMICAL SHEAR ZONES

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A lot of uncertainty remains about the exact nature of the geological mechanisms allowing mineralising fluids to flow from depth and form localised mineral deposits. Traditional assumptions of fluids travelling through highly permeable faults raise interesting questions about the existence of such open faults at depths below the brittle-ductile transition for example. In this contribution, we present the behaviour of impermeable shear zones in such environments, under specific conditions where temperature sensitive endothermal reactions trigger in-situ release of fluids that lubricates the fault and leads to their reactivation. The response of such systems can be of various nature, including slow creep, one-off reactivation events, or episodic reactivation events during which the permeability increases by several orders of magnitudes and allows fluids from depth to flow upwards. Such periodic events can be observed currently as episodic tremor and slip events in subduction zones and can also be inferred from spatial observations from exhumed megathrusts.

Three major driving parameters impact the system response: the Gruntfest, Lewis, and Damköhler numbers. We present the respective impacts of those parameters, along with numerical solutions to investigate the various stability regimes. This includes the open-source REDBACK simulator (https://github.com/pou036/redback), specifically developed to simulate this chemo-mechanical oscillator, as well as a pseudo-arclength continuation method based on REDBACK.

1040–1220
TUESDAY 20 FEBRUARY 2018

5E STRATEGIC AND INDUSTRIAL

INDUSTRIAL MINERALS – EVALUATION AND PROFITABILITY

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Industrial minerals are often misunderstood and misrepresented by the general community, education and research organisations, industry professionals and governments. They may best be defined as mineral and mineral concentrate products used in industrial and manufacturing applications. During production, their specific chemical and physical properties may be enhanced, though remain largely unchanged by any chemical processing.

Industrial minerals are commonly misperceived by technocrats and financial types alike as the poor cousin to precious metals, base metals, light metals and energy minerals. To the contrary, many small and large industrial mineral companies are highly profitable at 15–30% EBIT/Sales with strong returns on capital employed, including iron ore, potash and borates.

Effective exploration and evaluation of industrial minerals must recognise the principle of 'Value in Use'. This involves a dynamic interplay between technical, market and commercial factors, including resource characterisation, geometallurgy, application tests, customer trials and primary market surveys. Products require consistency of physical and chemical properties and performance in the customers' application.

Key profitability factors include technical understanding (not just JORC numbers), market knowledge, QA/QC discipline and key customer relationships. Success is rarely about having the biggest or the cheapest, it's more about consistency, rarity, functionality, market structures and barriers to entry.

All the buzz is about minerals and metals for the electronic, battery and sustainable energy industries. Key criteria and methods to evaluate, benchmark and create a highly profitable and sustainable business in lithium, cobalt, graphite, indium, manganese, scandium, beryllium, silicon or high-purity quartz are considered.

MINERAL DEPOSITS IN THE ONTARIO COBALT BELT

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Recent exploration by Battery Mineral Resources Limited has located numerous cobalt-arsenic-(silver, gold, nickel, copper) deposits in eastern Ontario. The deposits are located within a 250 km zone located north of Sudbury and trending east across the Quebec border. Deposit types include sulphide-carbonate vein systems, skarn, massive sulphide and sulphide breccia. This talk provides an update on the geology and exploration of several high-grade cobalt deposits within this belt.

THE SINCLAIR ZONE CAESIUM DEPOSIT, PIONEER DOME, WA

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During 2017 Pioneer intersected Australia's first significant intersection of pollucite in RC drilling, resulting in the definition of the Sinclair Zone caesium deposit, within 1 of 7 identified pegmatite suites with LCT mineral affinities that occur along the Eastern margin of the Pioneer Dome, Western Australia.

At the start of 2017, the Pioneer Dome was a clean slate in respect of LCT pegmatite knowledge. Using first principals, soil sampling and mapping, successive LCT pegmatites were identified and are now drill-ready.

The Company has been at the forefront of using modern techniques such as pXRF, SWIR and RAMAN to assist in its exploration advances.

1040–1220
TUESDAY 20 FEBRUARY 2018

5F EM INVERSION MODELLING

TRANS-DIMENSIONAL MONTE CARLO INVERSION OF SHORT PERIOD MAGNETOTELLURIC DATA FOR COVER THICKNESS ESTIMATION

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We have developed an algorithm and released open-source code for the 1D inversion of magnetotelluric data. The algorithm uses trans-dimensional Markov chain Monte Carlo techniques to solve for a probabilistic conductivity-depth model.

The inversion of each station employs multiple Markov Chains in parallel to generate an ensemble of millions of conductivity models that adequately fit the data given the assigned noise levels. The trans-dimensional aspect of the inversion means that the number of layers in the conductivity model is solved for rather than being predetermined and kept fixed. Each Markov chain increases and decrease the number of layers in the model and the depths of the interfaces as it samples.

Once the ensemble of models is generated, its statistics are analysed to assess the posterior probability distribution of the conductivity at any particular depth, as well as the number of layers and the depths of the interfaces. This stochastic approach gives a thorough exploration of model space and a more robust estimation of uncertainty than deterministic methods allow.

The method's application to cover thickness estimation is discussed with synthetic and real examples. Inversion of complex impedance tensor and also derived apparent resistivity/phase data are both demonstrated. It is found that the more pronounced layer boundaries allow more straightforward interpretation of cover thickness than that from deterministic smooth model inversions. It is concluded that thickness estimates compare favorably with borehole lithologic logs in most cases, and that the method is a useful addition to a range of cover thickness estimate tools.

COMPARATIVE ANALYSIS AND JOINT INVERSION OF MT AND ZTEM DATA

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Magnetotelluric (MT) data are typically broadband, covering 0.001 to >1000 Hz, but inter-site spacing is coarse. Airborne Z-axis tipper data (ZTEM) are denser but usually limited to frequencies >30 Hz. We analyse a pair of overlapping 3D surveys to examine lateral and vertical spatial sensitivity.

The MT data include a 2D line and a 3D survey. The line data also has magnetic tipper data that allows for a direct comparison with ZTEM; in the overlapping frequency range the agreement between the two magnetic data sets is good, with ZTEM showing higher lateral smoothness.

CGG's 3D MT-CSEM non-linear conjugate gradient inversion engine was extended to accurately model the ZTEM data, using measured sensor altimetry data and detailed 3D topography. Both single domain and joint inversions of the ZTEM and MT data were carried out. A suite of inversions were run to test the influence of starting resistivity and regularisation parameters on output models, carried out in exactly the same way for MT, ZTEM, and joint MT+ZTEM inversions to allow for direct comparison.

ZTEM single domain inversion results depend strongly on the starting resistivity value, confirming that the method maps relative variations rather than absolute resistivity values. Shallow lateral structure qualitatively agrees with the MT, while deep resistivity from ZTEM inversion is driven by model regularisation only. Joint inversion improved the relatively shallow section, calibrating the ZTEM resistivities and adding continuity between the MT sites. Below around 1,500 m, the 3D resistivity model is controlled by the MT data alone.

1, 2.5 AND/OR 3D INVERSION OF AIRBORNE EM DATA – OPTIONS IN THE SEARCH FOR SEDIMENT-HOSTED BASE METAL MINERALISATION IN THE MCARTHUR BASIN, NORTHERN TERRITORY

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The southern McArthur Basin in Australia's Northern Territory is host to some Tier-1 sediment-hosted base metal mineral deposits including the McArthur River Zn–Pb–Ag mine. Airborne electromagnetic (AEM) data sets have been employed as a key exploration technology in the search for these mineral systems. A geological interpretation of results arising from the use of different inversion techniques, including 1, 2.5 and 3D methods, was undertaken on a helicopter EM data set acquired over a structurally complex sediment package in the Batten Fault Zone north of the McArthur River Mine. The exploration targets were conductive, mineralised units (HYC pyritic shale member) associated with the Barney Creek Formation. Results from this study suggested that although the model fits were generally good, the derived conductivity models for the 2.5D and 3D inversions appeared to be smooth representations of geological reality, particularly when compared with data from drilling and surface geological mapping. Superficially, the 1D smooth model layered Earth inversions appear to map geological variability and structural complexity in greater detail even though the structures are more 3D in nature. IP effects are observed in the data and influence the modelled structure, but can be accounted for. The outcome of this study also indicates that when employing higher order inversion methods in the interpretation of AEM data sets, there may be significant benefit in asking a contractor/consultant for 1D inversion results as well. In the resulting interpretations if conductors appear in one but not the other, it is worth asking the question why?

SPATIALLY AND CONDUCTIVITY LOG CONSTRAINED AEM INVERSION

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We have developed an algorithm and released open-source code for 1D inversion of airborne electromagnetic data incorporating spatial and conductivity log constraints. The deterministic gradient based inversion algorithm uses an all-at-once approach, in which whole datasets or flight lines are inverted simultaneously. This allows spatial constraints to be imposed while also ensuring the inversion model closely matches any downhole conductivity logs that are near to the flight lines. The intent of the algorithm is to improve consistency along and across flight lines by taking advantage of the assumed coherency of the geology.

Instead of roughness constraints, 'sameness' constraints are used. To implement these the regularisation penalises differences between the conductivity of 1D model/layer pairs and the weighted average conductivity of every other neighboring 1D model within a user selected radius of their position. The neighbor averages are computed with inverse distance to a power weighting. The comparisons can be made over equivalent elevations or equivalent depths. Downhole conductivity log constraints are imposed in a similar fashion, by penalizing the differences between conductivity logs, averaged over selected intervals, with their respective neighboring 1D models. Overall the regularisation encourages the final 1D conductivity models to be as similar as possible to their neighbors and to conductivity logs.

It is demonstrated with real and synthetic data examples that the method enhances geological interpretation by improving the model's continuity along and between flight lines, and its match to conductivity logs.

1040–1220
TUESDAY 20 FEBRUARY 2018

5G REGIONAL MAPPING AND THOMSON OROGEN

AUSAEM; ACQUISITION OF AEM AT AN UNPRECEDENTED SCALE

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Exploring for the Future is a four-year program of the Commonwealth Government in which a significant component of the data acquisition phase of the project is the AusAEM Airborne Electromagnetic (AEM) Survey. This survey will focus on wide line-spaced acquisition as a regional mapping tool to gather new pre-competitive data and information, on an unprecedented scale. The objectives are to map, at a reconnaissance scale:

- Trends in regolith thickness, character, and variability.
- Variations in bedrock conductivity.
- The continuity of key conductive bedrock (lithology-related) conductive units under cover.
- The groundwater resource potential of the region.

The first AEM survey of this program will cover an area of over one million square kilometers, at a nominal line spacing of 20 km with infill lines spaced at 200 or 1400 m in selected areas.

In order to have the greatest impact the survey targets greenfield areas where the resource potential is unknown. The AEM data will contribute to estimating the thickness and variability of the cover material. To maximise industry collaboration on the project GA sought, and received, expressions of interest from explorers for infill flying on the regional survey.

Regional AEM surveys improve geological understanding in areas with little or no outcrop. The data enable informed interpolations between sparse drill-holes and estimates on the location of the model basement-cover interface information which reduces exploration risk. The new data will be released to the public domain at regular intervals to promote future activity by the exploration and research sectors.

APPLICATION OF AEM FOR COVER THICKNESS MAPPING IN THE SOUTHERN THOMSON OROGEN

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The southern Thomson Orogen is a poorly understood crustal element of northwestern New South Wales and Queensland. The Southern Thomson Project, a joint research project between Geoscience Australia, the Geological Survey of New South Wales and the Geological Survey of Queensland, is improving mineral systems understanding of this under-explored orogen to encourage mineral exploration investment. The Project includes new pre-competitive geological and geophysical data collection and interpretation to inform stratigraphic drilling of strategic crustal elements within the southern Thomson Orogen.

Two AEM surveys were flown in 2014 and 2016, respectively. Results from these were interpreted using available stratigraphic borehole data and surface geological mapping to produce a new cover thickness model of the area that is used to interpret target depths for the stratigraphic drilling, and to inform on the validity of other pre-drilling geophysical methods.

This presentation presents highlights of the AEM data and discusses its implications for mineral exploration as well as long-term landscape evolution, neotectonism within the Eromanga and Lake Eyre basins and hydrostratigraphic unit mapping within the region. Results of the modelling will demonstrate that large portions of covered ground are within reach of exploration drilling.

ESTIMATING COVER THICKNESS IN THE SOUTHERN THOMSON OROGEN – A COMPARISON OF APPLIED GEOPHYSICS ESTIMATES WITH BOREHOLE RESULTS

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The geology of the southern Thomson Orogen in northern New South Wales and southern Queensland is poorly understood. Basement geology is rarely exposed and there are generally many tens to a few hundreds of metres of overlying

unconsolidated or indurated Cenozoic and Mesozoic cover, largely consisting of Eromanga Basin rocks. These cover sequences are a significant impediment to mineral discovery and highlight the need for precompetitive data to be collected in this area to increase our understanding of the geological character and mineral potential of the covered basement geology.

Potential sites for up to sixteen stratigraphic boreholes designed to intersect the basement geology were selected using potential fields, solid geology interpretation, airborne electromagnetic data and local water-bore cover thickness information. Once these sites were selected, high resolution estimates of cover thickness (i.e. the thickness of regolith and/or sedimentary rocks overlying crystalline or metamorphic basement) were derived by applying refraction seismic, passive seismic and audio-magnetotelluric techniques, to more accurately determine cover thickness for accurate budgeting and drilling technical risk reduction.

A comparison of the estimates derived from the applied geophysical techniques with the actual cover thicknesses determined from borehole logs, together with an analysis of the uncertainties for each method, has highlighted the effectiveness of each geophysical technique. These new data and interpretations contribute to an Explorers' Toolkit of techniques to help reduce the risk to the exploration industry in searching for new mineral deposits in covered terrains in general, and in particular the underexplored terrain of the southern Thomson Orogen.

INCREASING PROSPECTIVITY IN A COVERED TERRAIN – THE SOUTHERN THOMSON OROGEN, NORTHWEST NSW

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Palaeozoic rocks of the southern Thomson Orogen form basement throughout northwest NSW and southwest Queensland, and potentially have similar mineral endowment to adjoining regions of the Tasmanides, including the base metal and gold mineralisation of the Lachlan Orogen to the south. The basement rocks are covered almost completely by Mesozoic sedimentary rocks of the Eromanga Basin within NSW, masking any prospective structural corridors and mineral systems. Several mineral exploration programs have penetrated cover in recent years, with a variety of targets sought, techniques applied, and some indications of mineralisation identified within the Thomson Orogen. However, overall the terrane is underexplored.

The collaborative Southern Thomson Project between Geoscience Australia, the Geological Survey of New South Wales and the Geological Survey of Queensland is advancing the understanding of tectonic history and mineral prospectivity beneath cover in the southern Thomson Orogen by acquiring and interpreting new geoscience data, including geophysical, geochemical, and isotopic investigations.

Regional Broadband MT traverses have been modelled across significant basement domains, showing deep crustal conductivity contrasts along major faults such as the Olepoloko and Mount Oxley faults. The timing of significant structures within the southern Thomson Orogen has similarities to those of adjoining orogens.

Age constraints are developing for key stratigraphic units identified from geophysical mapping. In the Cuttaburra area, a detailed study of geochronology and paragenesis has focussed on mineral system analysis and event timing. A drilling program to obtain core samples from a range of geophysical features is scheduled for completion in 2017.

1040–1220
TUESDAY 20 FEBRUARY 2018

5H GROUNDWATER CASE STUDIES

RATE OF SUCCESS FOR A GROUNDWATER DRILLING PROGRAM PLANNED FROM AEM, GASCOYNE RIVER, WA

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In a collaboration between Department of Agriculture and Food, Western Australia (DAFWA) and CSIRO, funded by the Western Australia Government's Royalties for Regions Program and the Gascoyne Foodbowl Project, the Gascoyne River AEM Aquifer and Groundwater Characterisation Project was established with the aim of determining whether airborne electromagnetic (AEM) data can be employed to better map attributes of the unconfined alluvial aquifer beneath and adjacent to the ephemeral Gascoyne River.

One major aspect of the project was to produce drilling targets, based on interpretation of AEM data, for groundwater production. In a previous presentation delivered at SAGEEP (2015), we explained our method of selecting 71 drill targets. In this presentation, we briefly recapitulate our method and discuss the result of the drilling campaign that ensued. We show that our exploration targets have resulted in overwhelming success in the conversion of exploration wells to production bores; and that the production wells produce greater yields of better quality groundwater than previous campaigns that were conducted through step-out drilling.

We also show that the interpretation of the AEM inversions allowed us to map the aquitard layers that define the bottom of the Gascoyne River Old Alluvium aquifer system, determine the extent of the saltwater intrusion from the nearby Indian Ocean, and to calculate the overall volume of the aquifer system. These calculations allow us to provide estimates of total groundwater volume contained in the aquifer for sustainable production.

GEOPHYSICAL INVESTIGATION TO SUPPORT CHARACTERISATION OF STRUCTURALLY CONTROLLED GROUNDWATER FLOW INTO AN OPEN PIT MINE

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Efficient dewatering operations rely on reliable predictions of expected inflow and likely water level behaviour. These predictions stem from the conceptual understanding of the hydrogeology of the area, which itself is derived from studies into the aquifer extents, hydraulic parameterisation and connectivity

with adjacent aquifer units. Due to their isolated and discrete nature, structural controls on these inputs to the conceptual understanding are amongst the most challenging to determine.

We present the findings of an investigation into structurally controlled flow into an open pit iron ore mine in the Pilbara region of Western Australia. Bore yields, groundwater salinity and water level behaviour of in-pit bores unmistakably indicated flows in excess of normal aquifer throughflow. Airborne magnetic data allowed regional identification of a potential lineament which was confirmed with high density grade control drilling results. These indicated the presence of a trough-like mineralised feature likely to enhance connection to a regional aquifer system down dip of the iron ore body or with a fractured rock aquifer beneath the ore body. A detailed ground magnetic survey was conducted along strike from the interpreted lineament, drastically improving on the aeromagnetic data, further validating the conceptualisation of the structure and providing greater spatial accuracy with which to target future hydrogeological works around the current pit. Subsequent modelling and reconciliation with closely spaced drilling information, including downhole magnetic susceptibility logging, increased the understanding of the basement magnetic response, and supports the use of the magnetic method for local hydrogeological studies.

UNCOVERING THE MUSGRAVE PROVINCE IN SOUTH AUSTRALIA USING AIRBORNE EM

Camilla Soerensen[1], Tim Munday[1], Carmen Krapf[2], Andy Love[3], Adrian Costar[4], Kent Invararity[4], Michael Gogoll[4] and Mat Gilfedder[1]*
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The presence of a thick and complex cover across many parts of Australia represents an impediment to effective and efficient minerals exploration. This is exemplified in the Musgrave Province of South Australia, a terrain highly prospective for magmatic Ni–Cu–PGE and IOCG deposits, where a transported regolith imposes a significant risk and challenge to explorers. Effective exploration through this region requires an understanding of that cover, its character and its spatial variability. This cover is also a source of groundwater that supports community and environment but our understanding of this resource is compromised by the limited information we have about it. To address these issues, two regional AEM surveys were undertaken across the Province involving the TEMPEST High Moment fixed-wing time-domain EM system (western part) and the SkyTEM^{304fast}, a helicopter time-domain EM system (eastern part). In excess of 16 000 line km were acquired, with a nominal line spacing of 2 km, orientated N–S. The inversion of these data and analysis of the results reveals a highly variable cover and a complex series of palaeodrainage systems with a notable litho-structural control on their orientation and distribution. These palaeovalleys are obscured by a valley-fill of Pliocene to Pleistocene sediments and overlying Quaternary sand dunes, and in the eastern region the observed conductivity structure suggests that this fill comprises a stratified aquifer system, which is supported by drilling. The study has generated a regional scale cover map which will aid the future exploration of the region, whist helping secure community and environmental water supplies.

A MULTIDISCIPLINARY STUDY OF GROUNDWATER CONDITIONS IN SEDIMENTARY STRATA AT THIRLMERE LAKES (NSW)

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The Thirlmere Lakes include five natural wetlands within a world heritage listed national park, where a decline in water levels has been observed over many years. Lake levels correlate with rainfall variability and are historically known to have dried several times during prolonged droughts. However, the cumulative effects of long term hydrological changes on the lakes are unclear, as are uncertainties associated with extraction of water for local uses and dewatering for longwall mining.

This study is part of a large multi-disciplinary research program, of which this part focuses on groundwater conditions in structured rock masses, and the possibilities of interactions with sediments below the lakes. Surface geophysical techniques and mapping of geological structures have been combined with deep drilling, wireline logging and investigations of sediment geology. Characterisation of sedimentary strata included permeability, bulk density, moisture content, porewater stable isotopes and XRD mineral identification. Two new deep drillholes were used to obtain information on hydraulic properties of formations. A staged geophysical survey program was designed to complement geological investigation, particularly to target sediment probing: resistivity imaging and ground penetrating radar to define heterogeneity within unconsolidated alluvium (clay and peat layers) and an indicative depth estimate to the underlying rock. A combination of these geophysical methods and contextural geological information, with magnetics/electro-magnetics attempted to determine the nature of structural anomalies, including infill materials and the extent of penetration of lineaments through rock formations. The results of this work provide a thorough evaluation of groundwater conditions in structured rock that underlie the sediments of Thirlmere Lakes.

1410–1500
TUESDAY 20 FEBRUARY 2018

6A PNG AND NZ

A METHOD FOR ASSESSING EARTH MODEL UNCERTAINTY IN THE TARANAKI BASIN, NEW ZEALAND

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Reservoir evaluation is often based on the interpretation of one seismic image. The amount of uncertainty associated with this image is unquantified.

When building an earth model tomographically there is inherent uncertainty as a number of models can all realise the same

measure of common image gather flatness. We present an analysis tool that quantifies that inherent image uncertainty.

Firstly, the maximum spatial resolution and recoverable velocity error of the tomographic velocity update is established using a classic checker-board test. Once the intrinsic resolution of the inversion process is established, a large population of perturbated models is generated from a given velocity model.

Secondly, migrations are performed for all perturbation models and residual moveout metrics generated. Finally, tomographic inversions are performed for all perturbations and are compared to the starting model to establish an inversion error.

Statistical analysis across all inverted models is performed for each grid location to reveal the mean, variance and standard deviation velocity. Additionally, a spatial reliability indicator is created to give a positional error envelope for the data. These model variance cubes and error envelope analysis are generated with the new workflow in the Taranaki Basin, offshore New Zealand.

The metrics can be directly used by interpreters to improve the reliability of their reservoir interpretation and can be used in conjunction with traditional seismic deliverables in mitigating risk associated with target positioning and volume. Additional information about the local illumination strength, for example, can be added to highlight any possible correlations between poor illumination and high model uncertainty.

MODELLING AND VISUALISING DISTRIBUTED LITHOSPHERIC DEFORMATION OF AUSTRALIA AND ZEALANDIA USING GPLATES2.0

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The recently released GPlates2.0 software (www.gplates.org) provides a framework for building plate models including distributed extension and compression, driven by the motions of the surrounding, rigid plate interiors, assimilating information from well and seismic data. Here we present a regional deforming plate model for Australia and Zealandia. It captures the progressive extension of all Australian continental margins, starting with the Jurassic extension of the Northwest Shelf, and including the extension of the southern and eastern Australian margins. The model also includes the extension of the Lord Howe Rise and southern Zealandia starting in the mid-Cretaceous, the subsequent complex compressional deformation of New Zealand since the early Miocene, and the orogeny along Papua New Guinea. The model allows a computation of lithospheric stretching factors for passive margins, as well as compression factors for orogenies. This allows the computation of crustal thinning/thickening through time of any point within a deforming mesh, either by starting with an assumed initial crustal thickness, or by using present-day crustal thickness as a constraint. The latter is suitable for basins, while the former is more applicable for orogens, where today's crustal thickness is not a good indicator for total crustal thickening due to erosion. The model can be combined with estimates of mantle-driven dynamic topography through time to generate basement subsidence or uplift models including isostatic and dynamic components, serving as boundary conditions for basin models as well as source-to-sink sediment transport models to provide improved constraints for resource exploration.

1410–1500
TUESDAY 20 FEBRUARY 2018

6B INTERNATIONAL

ON THE GEOTHERMAL POTENTIAL OF THE HEYUAN FAULT, SOUTH CHINA

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Geothermal energy potential in China is high, and although they currently lead the way in direct heat production, geothermal power generation is still low. Hot spring analysis and surface heat flux data indicate significant potential resources for the major industrial province of Guangdong, South China. This pilot study investigates the Heyuan Fault, Guangdong, as a potential site for a geothermal power plant. The study focuses on two principal hypotheses: (1) that there are preferred locations of hot spots at fault intersections and (2) that a combination of processes may be acting to contribute to the elevated surface heat flow.

We find that hot springs occur along the NE trending Heyuan Fault, clustering where NNW striking faults crosscut the Heyuan. The increased heat flow can be explained partly by radioactive decay of a large granite pluton beneath the fault, however, additional heat sources may need to be considered to explain the heat flow maxima of above 85 mWm^{-2}. We postulate that advective (topographically driven) and convective (deep fluids ponding at the brittle-ductile transition) processes may be operating to generate these heat anomalies.

Expansive quartz reef systems exposed on the Heyuan Fault are proposed here to represent uplifted sections of these deep fluid circulation patterns. A detailed systematical analysis of reef structures will reveal (1) the fluid provenance, (2) precipitation conditions and (3) deformation mechanisms, which will ultimately help us understand how fault intersection relations control fluid flow; which is of key significance if it can be utilised for targeting geothermal energy.

THE DISCOVERY AND DEVELOPMENT OF OIL RIM FIELDS IN THE BEIBU GULF, CHINA

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The Beibu Gulf is a prolific hydrocarbon province on the western coastline of China. The Miocene Jiaowei Formation contains thick sandstone sequences with excellent reservoir quality, a low degree of internal heterogeneity and excellent aquifer support. Structures are low relief causing many discoveries to be classified as thin oil rim fields (<15 m oil columns with bottom-water drive). These discoveries have moderate to heavy oils with low gas-oil ratios and moderate to high oil viscosities. The combination of these rock and fluid

properties are ideal conditions for rapid water coning, hence early well water breakthrough and low oil recovery factors. However, multiple fields in the Beibu Gulf significantly exceed pre-development production expectations. Closer inspection of core and log data indicates there is often a dolomitic alteration zone at the oil-water contacts with permeabilities typically 2 to 3 order of magnitudes lower than the hydrocarbon-bearing reservoir which act as effective aquitards to slow the onset of water coning. The diagenesis is theorised to be due to microbial decomposition of hydrocarbons at the oil-water interface which accrete dolomitic cements as a byproduct. Seismic inversion and amplitude mapping reinforce the view that the alteration zones are pervasive and flat-lying. Case studies are presented covering the discovery, development and production performance of three oil rim fields in the Beibu Gulf.

1410–1500 TUESDAY 20 FEBRUARY 2018

6C NON CONVENTIONAL

THE USE OF CORING INDUCED PETAL FRACTURES IN COAL TO SUPPLEMENT AND GROUND TRUTH THE INTERPRETATION OF ACOUSTIC AND RESISTIVITY IMAGE LOGS

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Resistivity and acoustic scanner image logs, in both the CSG and coal-mining industries, are the predominant means of determining azimuths of joints/cleat in coal. Resistivity images of the bore wall reveal large fractures that intersect the entirety of the bore wall (represented by a sinusoidal traces), and those have low height and intersect one side of the bore wall (represented by lineations). Acoustic image logs often only record the larger-scale features.

The strike of fractures that appear on an image log as a lineation are mostly apparent rather than true. In some instances all lineations are presented on rose diagrams as true azimuths, and lineations are erroneously treated as poles to a fracture. Both produce misleading results. A statistical method that extracts the true azimuths from a weighted mean of apparent azimuths, as well as the mean azimuths of highest apparent dips is presented. This is of value to interpreting local tectonic history and gas production.

Petal fractures (PF) in coal, when combined with breakout information, can also be used to determine joint/cleat azimuths of both large and small scale fractures. The PF core-based method can be limited by the presence and abundance of PF, and is dependent on restoring segments of core to their correct relative orientation. Bedding-plane observations of core provides cleat/fracture information not obtainable from an image log. The PF core-based method, in combination with bedding-plane observations of cleat and joints, provides a means to ground truth the results of both acoustic and resistivity image log analysis.

AUTOMATIC FRACTURE IDENTIFICATION USING X-RAY IMAGES

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Unconventional energy (shale gas, shale oil, tight gas, coalbed methane) are trapped in low porosity/permeability environments and are difficult to produce. While the US economy booms due to the shale gas production, rest of the world with nearly 7000 trillion cubic feet of shale gas reserves hasn't been able to unlock the potential of shale gas, yet. Given the technological advancements, the big question is – Are we missing the science? We address this unconventional resource challenge by combining a recent multiphysics, multiscale geomechanics theory with laboratory and modern computational assisted petrophysics and material science concepts. This solid science base will build the platform for enabling a data intensive paradigm for the resource industry. To this end we use of a finite element, Multiphysics Object-Oriented Simulation Environment (MOOSE, http://mooseframework.org) open source software originally designed for multiscale simulations of a nuclear reactor. Using MOOSE, we aim to incorporate multiphase flow in the presence of viscous and plastic processes within the reservoir. Our new simulation platform for the petroleum industry is also available as an open-source parallel simulator for Rock mEchanics with Dissipative feedBACKs (REDBACK, https://github.com/pou036/redback). Early attempts of modelling sand production in a geo-pressured reservoir in Papua New Guinea using REDBACK has been successful. In our current work, we aim to build a tightly-coupled benchmarked reservoir simulator which will highlight the impact of geomechanics on reservoir modelling. This novel approach to incorporate time-dependent geomechanical evolution of the reservoir and its effect on multiphase flow simulations is dubbed, 'Next Generation Reservoir Engineering'.

1410–1500 TUESDAY 20 FEBRUARY 2018

6D GEOCHEMISTRY

21ST CENTURY EXPLORATION GEOCHEMISTRY – THE GOOD, THE BAD AND THE UGLY

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'The Good, the Bad and the Ugly' film of 1966 revolves around gunslingers competing to find fortune of gold amid the chaos of the American Civil War. This scenario is not dissimilar to current exploration geochemists' objectives in the turbulence of an extended economic down turn. The film is also distinct in the use of long shots and close-up cinematography, as well as violence, tension, and stylistic gunfights. Again, not dissimilar to the multiple exploration scales we work with, the pressure to get results and the various technical tools one employs to achieve these results. The 21st century has seen some major developments that have shaped the manner in which exploration

geochemistry is conducted. Some of these are good, some are negative and some are downright ugly. More recent advances and future developments can be categorised in four key areas: (1) understanding metal mobility and mechanisms, (2) rapid geochemical analyses, (3) data access, integration and interoperability, and (4) innovation in laboratory-based methods. This presentation will highlight examples in these key areas with the related comparison to the good, bad and ugly aspects of each. Finally, we will look to avoid the hangman's noose by recognising the challenges and identify the frontiers that the exploration geochemistry community needs to traverse to find the next deposit (or buried cache of Confederate gold).

1410–1500 TUESDAY 20 FEBRUARY 2018

6E INDUSTRIAL – SANDS

FRAC SAND SUPPLY AND DEMAND AUSTRALIA

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Natural gas is an essential commodity for modern Australia. It's needed for power generation and is an indispensable feedstock for manufactured products such as fertilisers, plastics and chemicals. The distinction between 'unconventional' gas and 'conventional' gas is simply based on the type of rock the gas is found in. Both 'conventional' and 'unconventional' natural gas is methane. CSG and shale gas is almost pure methane whereas conventional gas may also contain ethane, propane, butane, and other hydrocarbons. Gas demand in eastern Australia continues and will increasingly need to be supplied from unconventional sources such as coal seam and tight shale gas formations which generally need the use of hydraulic fracturing techniques to allow the economic extraction of gas. Frac sand competes with ceramic proppants that are all imported. Frac sand must meet the tight specifications outlined by API RP-56. Key factors include: crush resistance, sphericity/roundness, acid solubility and sising. The demand will rise as more production holes are commenced to stimulate gas production in the years ahead. Only ~4% of coal seam gas holes in the Surat Basin have needed frac sand in recent years, but this is expected to rise to 40% within three years. The frac sand grade used is primarily 20/40# with smaller quantities of 16/30#, 40/70# and 70/100# making up the balance. There are few producers of frac sand in Australia. Logistics is a key component of the delivered price. There is a trend towards the end users preferring delivery in pneumatic tankers.

HIGH-GRADE SILICA SANDS IN THE EASTERN MURRAY BASIN NSW

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Investigations in 1979 defined a sand resource at Wah Wah of suitable colourless glassmaking sand. In December 2016 further drilling infilled some of the previously drilled area and extended to new areas.

From this drilling coloured and white sand resources have been defined, under a clay unit. The recent work suggests that the white sands may be of beach origin rather than fluvial.

White sand, defined by the 0.050% Fe_2O_3 contour, coincides generally with higher yield, mostly underlying 6 m to 8 m of clay – the thinner overburden.

Estimated resources are shown in Table 1.

Table 1. Resources summary

	All sand	White sand				
	In situ	*In situ*	Yield <0.710 >0.075mm	Product	$\%Fe_2O_3$	$\%Al_2O_3$
Area (m^2)	1 242 000	669 000				
Overburden clay (m^3)	11 000 000	6 360 000				
Sand quantity (t)	25 000 000	15 000 000	58%	8 700 000	0.035	0.20

These resources are Indicated Resources for JORC 2012 reporting, are defined by drilling and testing, and are suited for glass and other uses.

From the investigations a number of processing techniques can be employed dependant on user requirements. After the 2016 work an attrition-gravity process will be suitable, and cheaper than other options.

Based on results, the sand appears to be suitable for other products, including filter media, various construction uses, and other applications depending on markets.

Compared to the resource defined in 1979 the deposit is expected to be suited to:
- Selective extraction,
- Reduced focus on one market,
- By-products increasing overall yield,
- Lower cost treatment for the higher value products,
- Certainty that sufficient resource will meet longer term needs for a range of products.

1410–1500 TUESDAY 20 FEBRUARY 2018

6F EM INVERSION MODELLING

LARGE SCALE 3D AIRBORNE ELECTROMAGNETIC INVERSION – RECENT TECHNICAL IMPROVEMENTS

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The level of sophistication of 3D airborne electromagnetic (AEM) inversion software continues to advance in modern times. Coupled with data acquisition improvements and the rise in parallel computing, the capability of large scale 3D AEM inversion modelling for both time and frequency domain data is

reaching new heights. This work will highlight specific technical improvements that have facilitated this movement. It will also provide the necessary background information for the accompanying abstract that presents a field example showcasing 3D inversion results from an orogenic gold setting.

Key factors that have advanced 3D AEM inversion in recent years are the separation of forward meshes from the inverse mesh, the use of direct solvers on adaptive octree meshes and the strategic optimisation for massive parallel implementation. This work will address how each of these have contributed to 3D AEM inversion improvements and a synthetic model will highlight the benefit of 3D inversion for such targets as dipping plates. The abstract will also discuss how selectively down-sampling based on data gradients can reduce the number of observations without greatly affecting the overall model result. Finally, we demonstrate the effect of increased signal to noise ratios from modern acquisition systems and how this results in improved inversion models.

3D TIME-DOMAIN AIRBORNE EM INVERSION WITH FINITE-VOLUME METHOD

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Imaging and stitched 1D inversion algorithms for airborne EM data interpretation have been very effective in quasi-layered earth environments, but fail in steeply dipping geology and for compact 3D targets. Conventional time-domain 3D inversions consume lots of computer time, even when the discretisation is very coarse. Most of this time is taken for forward modeling and calculation of the sensitivity matrix. We present here an effective 3D time-domain airborne EM inversion based on the Gauss-Newton method.

We directly calculate the time-domain secondary field with the finite-volume method, which method is compact and thus greatly decreases calculation time. We apply several methods and techniques to speed up inversion: (1) we use a local mesh where fine cells are located near the center and coarse ones towards the edges; (2) the multi-frontal massively parallel sparse direct solver is employed to solve equations with multi-channels; (3) we use the adjoint forward method to obtain elements of the sensitivity matrix, and (4) we calculate the local sensitivity for each individual transmitter before re-combining them to form a complete sensitivity matrix. Finally, (5), for each iteration, we update the model using the preconditioned conjugate gradient method.

Using forward models and survey data, we show that our 3D time-domain airborne EM method achieves computational efficiency and obtains good inversion results.

1410–1500
TUESDAY 20 FEBRUARY 2018

6G REGIONAL COBAR

METAMORPHISM AND MINERALISATION IN THE COBAR BASIN: IMPLICATIONS FOR EXPLORATION

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The c.420 Ma Cobar Basin is a major mining province in central New South Wales with an estimated metal endowment exceeding 134.9 t Au, 1.91 Mt Cu, 3.46 Mt Zn, 1.8 Mt Pb and 3832 t Ag. Sedimentary sequences of the Cobar Basin preserve diagenetic to burial-related metamorphic grade. Inversion of the basin c.380 Ma resulted in localised penetrative cleavage development and epizone hydrothermal metamorphic grades developed around high-strain reactivated faults and shear zones. Mineralisation in the main Cobar mineral field is associated with these high-strain zones and is linked with hot structurally controlled fluids. South of the main Cobar mineral field, hydrothermal metamorphic highs are associated with correlative mineral deposits in areas of comparatively lower strain (Nymagee and Hera). These deposits are proximal to similar fault systems as those within high-strain zones. New data show that these southern deposits are in part stratigraphically controlled skarns, with early high-temperature (T) mineralogy preserved due to limited syn-inversion retrogression. Carbonate clasts are preserved in the lowest-T skarn and, combined with the regional distribution of ore bodies at a similar stratigraphic level, is suggestive of a regional slump horizon that has focused high-T mineralising fluids. High thermal contrast between anchizone 250°C basin sedimentary rocks and 500°C skarn alteration likely reflects a proximal magmatic heat source, and isotopic data are consistent with a mixed magmatic/basin fluid/metal source. A skarn origin for mineralisation in the southeastern Cobar Basin has implications for exploration, combining elements of both stratigraphic and structural control on the Cobar mineral system.

COBAR DEPOSITS – STRUCTURAL CONTROL

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The Cobar Superbasin is a highly mineralised Palaeozoic basin located in the Central sub-province of the Lachlan Orogen in Eastern Australia. The term Cobar Superbasin is introduced to refer to a series of deep-water troughs/basins, inferred to have formed as half graben and shallow water shelfs. Its northern portion is dominated with siliciclastic sedimentary sequences whilst the southern portion comprisesofsediments, volcaniclastics, volcanic rocks, granites and minor limestone.

The basin formed in the Early Devonian by NE-SW transtension and closed by NW transpression in Late and Middle Carboniferous Period. The overall inversion structural style is NW–SE folding overprinted by NE–SW trending and NNW-

trending eastwards oblique left-lateral reverse faulting in a combined thick- and thin-skinned tectonic environment.

The Cobar Style mineralisation is a common name for mineral deposits hosted in Cobar Superbasin and includes; massive sulphides (VMS), clastic hosted Pb–Zn mineralisation and epithermal gold.

Primary deposit location is controlled within the basement architecture including:
- basin marginal faults (growth faults);
- intersection of growth and transform/transfer faults; and
- intersection transform/transfer faults;

Secondary control of the deposit related to its geometry is caused by inversion tectonic:
- intersection of reactivated growth and transfer/transform faults;
- termination and deflection of strike-slip faults;
- overlap of en-echelon strike-slip; and
- junction of major faults.

Cobar Style mineralisation occurs in in an en-echelon array of sheeted veins characterised by a narrow width (5 m – 10 m), short strike (50 m – 10 m) and a significant depth extension (>2000 m).

1410–1500 TUESDAY 20 FEBRUARY 2018

6H INNOVATION

SOURCE ASSISTED MARINE REFRACTION MICRO-TREMOR (REMI) FOR MARINE MATERIAL STRENGTH ASSESSMENTS – NEW IRELAND PROVENCE, PAPUA NEW GUINEA

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Refraction Micro tremor (ReMi) is a relatively new technique which utilises ambient noise generated from urban infrastructure in addition to the natural seismic events to generate shear wave models of the subsurface. Work has been undertaken using ambient seismic data on land, however only very minor work has been undertaken to gain similar information within a shallow marine environments. This paper presents the field acquisition parameters, problems and limitations of data collection and results of a survey conducted in a shallow marine harbour in PNG. The primary objective was to undertake an assessment of the viability of marine ReMi to obtain subsurface parameters to assist in an overarching geotechnical study taking place onsite. The subsurface parameters that the investigation was aiming to define included shear strength and stratigraphy. The environment in which this trial was undertaken was a shallow marine environment containing paleochannels, coral, marine sediments and landslide material.

Material properties are extremely important during design of all engineering projects including seawalls and land reclaiming projects. Until recently there have been limited techniques that could provide S-Wave velocities within a shallow marine environment, with those available being limited to borehole techniques. The application of ReMi has the potential to allow for continuous S-Wave velocities and liquefaction calculations in a shallow marine environment.

The aim of the paper was to undertake research and development into the collection parameters of marine ReMi and attempt to optimise them for use in shallow marine engineering projects.

BOOTSTRAPPING RELIABLE NOISE MEASURE IN TIME-GATED NUCLEAR MAGNETIC RESONANCE DATA

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Time gating is a commonly used approach in the preprocessing of nuclear magnetic resonance (NMR) data before Laplace inversion. Gating suppresses spurious signals that can degrade recovered decay time distributions and therefore often stabilises inversion. However, care must be taken in applying this technique to real world data where both non-Gaussian and correlated noise decrease the efficacy of noise reduction through stacking. If not properly accounted for, unreliable noise estimates introduce inversion artefacts. Fortunately, noise realisation proxies obtained through data phasing can be used to bootstrap reliable confidence intervals for the windowed data. Benefits of the approach are demonstrated through inversion of synthetics as well as borehole data from a deep carbon capture and sequestration application as well as surface NMR data applied to near surface groundwater characterisation. We also introduce an open source cross platorm data processing utility with these capabilities which interested persons can use to explore the impacts of various processing workflows.

1530–1710 TUESDAY 20 FEBRUARY 2018

7A PNG AND NZ

INVESTIGATION OF POSSIBLE SHALLOW GAS ACCUMULATIONS ASSOCIATED WITH POCKMARKS ON THE OTAGO SLOPE SOUTHEAST OF NEW ZEALAND

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High-resolution 'boomer' seismic data, together with an industrial 3D seismic dataset indicate the possible presence of shallow gas in the vicinity of the Waitaki Canyon, SE of New Zealand's South Island. Crescent-shaped seafloor depressions are abundant on the marginal extent of the Otago canyon system in water depths between 500 and 1100 m. Fluids seeping through the seabed, potentially forming pockmarks, play a crucial role in seabed ecological systems and can be used to investigate the distribution of hydrocarbons in underlying geological units. Recently acquired 3D seismic data, which characterise the Barque prospect in the Canterbury frontier basin, exhibit the first

indications of shallow gas in the region. Two areas with shallow high-amplitude reversed phase reflections were identified and targeted for a high-resolution 2D seismic survey. The 2D data, acquired by the University of Otago in 2017, show reduced amplitudes beneath the bright spots (as also observed in the 3D data). Above the bright spots, bathymetry data show crescent-shaped seafloor depressions, which were most likely modified by northward flowing currents. Both recent and buried seafloor depressions along the shelf exhibit the same northward facing crescent form that we associate with water current modification. Water column imaging data reveal no evidence for present-day seepage of gas through the seabed. An ongoing program of 2D seismic and bathymetry data collection is underway. High-density velocity analysis and amplitude variations with offset (AVO) will be assessed around the bright spots using several in- and crosslines from the 3D data.

CHARACTERISATIONS OF FOCUSED GAS HYDRATE ACCUMULATIONS FROM THE PEGASUS BASIN, NEW ZEALAND, USING HIGH-RESOLUTION AND CONVENTIONAL SEISMIC DATA

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Gas hydrates are reported widely in seismic data from New Zealand's Hikurangi Margin (east coast of the North Island). Over the last decade, conventional petroleum exploration interests in this region have led to the collection of several regional seismic datasets. These data have greatly improved our understanding of hydrate accumulations in the area; however, the resolution of industry multichannel seismic surveys is limited by the bandwidth of the airgun sources used. We present results from an academic high-resolution generator-injector (GI) airgun seismic survey, undertaken in mid-2015, that targeted focused gas hydrate accumulations lying within thrusted accretionary units in the Pegasus Basin, at the south end of the Hikurangi Margin. Each feature was surveyed with 5 to 10 closely spaced seismic lines that provide an opportunity to examine the three dimensional structure and stratigraphy with better resolution than the original lines.

Two main processes of natural gas migration and resulting accumulation as hydrate are examined more fully: (1) vertical transport into the shallow seafloor driven by overpressure and (2) inclined transport upward along dipping permeable beds. In both of these cases, our data show significant three-dimensional variability is needed to focus fluid migration from below into hydrate trapping configurations within the hydrate stability field nearer to the seafloor. Due to the absence of well data in this basin, the high-resolution seismic data also help to constrain interpretations of basin stratigraphy which plays a significant role in hosting and trapping hydrate accumulations.

COMPARING SHALE GOUGE RATIO AND JUXTAPOSITION ANALYSIS USING STOCHASTIC TRAP ANALYSIS: EXAMPLES FROM GIPPSLAND, TARANAKI, OTWAY AND SOUTHERN NORTH SEA BASINS

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Exploration fault seal analysis of prospects is often focused on generating a probability of success. This risking considers sealing hydrocarbons against faults over geological periods of time, rather than production time. Typically the risking is based on cross-fault juxtaposition and/or sealing shale development on the faults, on a single 'best' technical model, commonly referred to as a deterministic model. Considerable work has been done by a number of workers to calibrate the sealing shale development, for example, the Shale Gouge Ratio (SGR) algorithm, to predict free water contacts. These calibrations involve back-calculating the seal potential as SGR and determining a resulting across fault pressure difference (AFPD), to trap an observed free water level. Importantly, this back-fitting of SGR and AFPD has been conducted on single 'best' technical models. In general, application of SGR methods on sealing across faults in prospects increases predicted column heights and enhances pre-drill chance of success. Prospects with large columns are typically generated and then discounted through geologic risk factors. If wells do not find the predicted columns, this is often 'explained' by lack of charge or trap breach. It is proposed that the fault and stratigraphic uncertainties are significant and need to be included in the modelling of fault seal risk and inferred column heights. A process of model validation will be presented in which observed free water levels are compared with the results of single 'best' technical versus probabilistic models for both juxtaposition and SGR. Case studies from the Gippsland, Taranaki, Otway and Southern North Sea Basins show that probabilistic models can accurately predict free water levels (sub 10m accuracy) and identify leaking faults. Probabilistic models better predict free water levels and are thus better define prospect fault seal risk than models such as SGR based on back-calculating from single 'best' technical models. Incorporating uncertainties in a stochastic analysis typically yields smaller but much lower risk traps, rather than high risk traps based on overly optimistic calculations. Applying these models and methods to fault seal analysis will allow explorers to better define risks and rewards on prospects.

NEW REGIONAL DATA AND ADVANCES IN UNDERSTANDING OF THE STRATIGRAPHY, TECTONICS, STRUCTURE AND PROSPECTIVITY OF THE GULF OF PAPUA (PAPUA NEW GUINEA)

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Between 2015 and 2017, Searcher Seismic acquired 32 478 km of long offset PSDM 2D seismic data and reprocessed an additional 12 972 km of previously acquired 2D data in the Gulf of Papua, Papua New Guinea (PNG). The new data has resulted in a significant improvement in subsurface imaging and areal coverage, providing the foundation for a new integrated analysis of the region. In addition, a regional drop core geochemistry and heat flow survey provides important clues regarding the existence of working petroleum systems in the Gulf of Papua. The evaluation of these new datasets has improved the current understanding of the stratigraphy, plate tectonics, local structure petroleum prospectivity of the Gulf of Papua.

New seismic allowed identification of several depositional packages that are often bounded by regional unconformities related to the tectonic development of the area. Seismic and shipborne gravity/magnetics analyses allowed a confident identification of the following events/packages:

- Moho event allowing estimation of the crustal thickness and differentiation between oceanic and crust and calibration of the heat flow measurements;
- Paleozoic severely folded succession analogous to eastern Australia accretionary terrains;
- Permian analogous to the Bowen Basin in Queensland, Australia;
- Triassic to Jurassic succession supported by the existence of the Jurassic seep identified by the Davaria geochemical survey;
- Presence of previously unidentified block faulted highs with Miocene reefs and carbonate platform build-ups;
- Pliocene and younger basin sandstone floor fans; and
- Extension of the compressional front into deep water Gulf of Papua.

These observations have been integrated into an updated plate tectonic model that predicts widespread deposition of the Permian and Triassic to Tertiary source rocks estimated to be often within the hydrocarbon generative window.

1530–1710
TUESDAY 20 FEBRUARY 2018

7B INTERNATIONAL

SHELF-MARGIN ARCHITECTURE AND SHORELINE PROCESSES AT THE SHELF-EDGE: CONTROLS ON SEDIMENT PARTITIONING AND PREDICTION OF DEEP-WATER DEPOSITION STYLE

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The Lower Barrow Group (LBG; Latest Tithonian – Early Valanginian) is a shelf-margin that prograded during a late phase of rifting under various subsidence regimes and supply-dominated conditions. A 3D semi-automatic, full-volume seismic interpretation method allow identifying high-order clinothems presenting an estimated cyclicity of ~40 000 years, in which a quantitative analysis of the shelf-margin architecture and shorelines processes was conducted. Overall, three and four main types of hydrodynamic regimes and deep-water systems were identified, respectively.

Falling to flat shelf-edge trajectories are associated with sediment bypass, whereas rising shelf-edge trajectories are linked with increasing sediment storage on the shelf. While fluvial to wave processes can be dominant in all A/S conditions, results show that fluvial-dominated coastlines are associated with steep high-angle slope clinoforms and short to longer run-out turbidites. Conversely, wave-dominated coastlines are linked to low-angle slope clinoforms and poor turbidite system development (occasional sheet sand and MTDs).

The short and longer run-out turbidite systems present a tripartite architecture (canyon/slope valley; channel; lobes), which mostly appear as short-lived, vertically/laterally stacked elements fed by multiple small rivers forming linear ramp systems. Due to the shallow configuration of the margin (<500 m), the presence of short slopes and overall high sand-to-mud ratio, the turbidite systems are smaller scale (<50 km) and probably shorter lived than most modern turbidite systems (100–1000 km).

This study sheds new lights on the significant role of shelf-margin architecture (slope gradient, hydrodynamic regime) in predicting the deep-water sediment delivery behavior (sediment partitioning, type of deep-water system).

SEDIMENTARY CHARACTERISTICS AND LITHOLOGICAL TRAP IDENTIFICATION OF DISTANT BRAIDED RIVER DELTA DEPOSITS: A CASE ON UPPER CRETACEOUS YOGOU FORMATION OF TERMIT BASIN, NIGER

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Lithological trap identification in thin sand and thick shale layers is still a challenge for hydrocarbon exploration. Based on the high-resolution sequence stratigraphy theory and the establishment of high resolution sequence stratigraphy framework with seismic-well tie, the dynamic deposition process of braided river delta sands on late Cretaceous Yogou formation has been analysed on 62 wells in passive rift Termit basin with multi-stages depressions and reversals. (1) Six kinds of sedimentary microfacies and three major reservoir sands are in Yogou formation; (2) Based on accommodation space/sediment supply change and the deposition progress, sedimentary facies distribution in each member of YS3 sub-formation has been done according to sands thickness statistics of sedimentary micro-facies, narrow-time seismic attributes and slices analysis, the multi-sources and distant braided river delta depositional model has been concluded; (3) Based on source rock and caprock evaluation, with reservoir sands distribution and faults impact on Yogou formation of Termit basin, structure-lithology traps, structure-stratigraphic traps, stratigraphic traps and lithology traps are concluded. Traps influencing factors, i.e., structure geometry, sands distribution, paleotopography, stratigraphy cycling, sand/shale lateral connection, reservoir quality and so on, have different impacts on these traps, and different lithologic-stratigraphy traps have different exploration risks.

AIRBORNE GRAVITY GRADIOMETER SURVEY OVER THE PELARANG ANTICLINE, ONSHORE KUTAI BASIN, INDONESIA

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The Pelarang Anticline is part of the NNE-SSW oriented Samarinda Anticlinorium, a detached thrust-and-fold belt in the Tertiary Kutai Basin. Results from an airborne gravity gradiometer survey over the Pelarang Anticline are presented herein.

The Pelarang Anticline is interpreted as a detachment fold ~30 km long with steeply dipping (70°–80°) flanks. However, seismic imaging on existing 2D data is poor.

In October 2016 Cue Energy acquired airborne gravity gradiometer survey data over the anticline. The survey revealed a large (~10 mGal) gravity signal range, and that the anticline is associated with a strong, positive gravity anomaly. Subsequent application of potential field enhancement filters clearly delineated the crest and the flanks of the feature.

2D modelling of selected profiles across the anticline suggests that it can be modelled as a 1500 m – 2000 m wide, by ~2000 m high shale body that is close to breaching the surface in places. This is in alignment with an interpretation that the feature is cored by a shale diapir, resulting in un-prospective areas.

However, 3D modelling has revealed significant along-strike variations in the depths to the crest of the anticline, suggesting the presence of several anomalous structural lows. Further investigation suggests these features are pull-apart mini-grabens, formed in response to localised shear movements. At least two commercial hydrocarbon accumulations, Sambutan and Mutiara, appear to be genetically related to the newly recognised structural anomalies.

This survey has led to the recognition of a new exploration play in the region, and provided a tool to pursue it.

THE EFFECT OF DEEP BURIAL AND FOLDING ON SANDSTONE RESERVOIRS IN GIANT GAS FIELDS, SOUTH AMERICA

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The underthrust fold belt of the Andes contains some very large gas fields in which the Lower Palaeozoic Sandstone reservoirs are buried to depths of over 4-6 km. The foreland depositional environment received high amounts of metamorphic and igneous rock fragments and deep burial was accompanied by substantial tectonic folding and fracturing. The combined effects of temperature, pressure and time on these labile sediments have reduced typical porosities <5% and matrix permeabilities <1 mD so that these reservoirs are ultra-tight and effectively unconventional. Nevertheless, the fields contain very large recoverable amounts of gas with minor liquids per well and they provide an intriguing case study that contrasts with the typical concept of a petroleum prospect and pose the question how many more large gas fields fit this model?

These complex structural fields required modelling by 3D-Geo using fractured and folded simulation models. The micro-porosity and micro-permeability has been investigated by Curtin University specialists using nano-scale special core analysis in an attempt to identify where the hydrocarbons reside in these rocks, how do they migrate out on production, and how best to estimate and optimise ultimate recovery?

High technology characterisation included TIMA-SEM to map mineralogy and texture at the nano-scale; X-ray Micro-CT analysis of 3D microstructure; NMR, ultra-low Helium porosity and permeability, Hg injection for capillary pressure; elastic and electrical properties to tie the seismic and log data for the modelling. Tri-axial tests helped understand the structural and tectonic history and its relation to the burial history of the reservoirs.

1530–1710
TUESDAY 20 FEBRUARY 2018

7C NON CONVENTIONAL

FRACCING ONSHORE AUSTRALIA

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Recent history has seen major inquiries in the Senate and under the control of several States and Territory Governments where one aspect involved the oil and gas exploration technique of fraccing.

Each and every inquiry has concluded that the technique is safe for the purposes of petroleum extraction, subject to appropriate scientific and technical regulation over the activity.

The paper covers the more significant negative submissions made to those inquiries by a range of providers and then explains why those submissions lack scientific and technical support. Such conclusion can only be that it is time for political intervention with science to be abandoned for the long term benefit of Australia and its energy requirements, not only on the east coast.

Each of these inquiries has focused its attention to onshore petroleum activities, but the technique is also commonly used offshore in tight sands and shales.

The paper will include a brief section to define what is fraccing and how the activity has been applied onshore Australia, rather than as applied to the massive fraccs in the major shale basins in the USA.

Submissions have been made by groups such as Lock the Gate, elements of the green movement in Australia, doctors and farmers. Few of these submissions have been founded on sound scientific principles, but that does not make them any less interesting to us or politically less powerful.

IMPACT OF ARTIFICIALLY MATURED ORGANIC MATTER ON THE DIELECTRIC AND ELASTIC PROPERTIES OF COMPACTED SHALES

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Organic material in shale formations contrasts greatly with the mineral matrix. It has a lower density, hydrophobic properties, higher compressibility than any mineral and by comparison with neighbouring minerals is an electrical insulant. With these characteristics organic matter (OM), even when present as only a small weight fraction, influences greatly the overall physical properties of a formation.

We developed a methodology in an attempt to reproduce OM found in shale source rocks with different maturity levels, kerogen types and particle sizes. The process notably comprises a heating phase in anoxic conditions with water and swelling clays. The resulting material is tested elastically and dielectrically by itself and then incorporated in a mineral matrix. It allows us to assess both the intrinsic properties of the OM and its influence in a natural-like scenario with comparison to control samples.

To create our artificial samples we develop a novel apparatus that includes a compaction cell that keeps track of porosity, density, expelled pore fluid and is equipped with P- and S-wave ultrasonic transducers to compute elastic moduli continuously. It also presents the possibility to produce several CT-scan images at different compaction levels to follow the evolution of fabric, homogeneity and organic particles distribution.

Our study aims to analyse the relationship between OM distribution and the anisotropy of elastic and dielectric properties. The effect of maturity level on the OM intrinsic properties and its influence on dielectric permittivity and P-wave velocity is also investigated.

THE STRATIGRAPHIC ARCHITECTURE, DISTRIBUTION AND HYDROCARBON POTENTIAL OF THE ORGANIC RICH KYALLA AND VELKERRI SHALES OF THE UPPER ROPER GROUP (MCARTHUR BASIN)

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The laterally extensive Mesoproterozoic Velkerri and Kyalla organic rich shales of the Roper Group in the McArthur Basin have been identified as possibly one of the most prospective shale gas plays in Australia. The Velkerri and Kyalla shales occur within a thick, predominantly marine, clastic succession within the upper Roper Group of the McArthur Basin in the Northern Territory. Santos has implemented regional studies across the McArthur Basin focussing on the tectonic setting, depositional models and sedimentological/stratigraphic relationships of the Roper Group to better understand the prospectively of the Velkerri and Kyalla shale gas plays. The review involves the study of open file drill core, well log analysis, seismic interpretation as well as the integration of available potential field data. The studies have provided an insight into the facies relationships across the full spectrum of shallow water to deeper marine deposits and the regional distribution of the main stratal units of the upper Roper Group. The Roper Group succession consists of approximately six major regressive–transgressive (R–T) sequences, each ca 500–1000 m thick, deposited in a clastic-dominated marine deltaic setting. This analysis focusses on the three youngest R–T sequences. The regional seismic interpretation reveals an overall southeast thickening of the upper Roper Group succession in the Beetaloo and OT Downs sub-basins, supporting a northward prograding delta depositional model. Well and seismic data indicate that the organic rich shales of the Velkerri and Kyalla formations are laterally continuous, relatively undeformed and thermally mature, classifying them as unconventional reservoirs hosting potentially large volumes of retained hydrocarbon.

GEOMECHANICAL PRESTACK DEPTH MIGRATION OF THE KRAKEN 3D (BROWSE BASIN, AUSTRALIA)

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Conventional pre-stack depth migration applied to the broadband Kraken 3D Marine Seismic Survey was unable to fully resolve short-wavelength velocity anomalies below the sea floor causing obvious imaging problems and limiting depth conversion and amplitude interpretation. Improved imaging was achieved by initiating tomography using a velocity model built by combining geomechanics with rock physics appropriate for shallow carbonates and mudrocks.

3D gravity modelling using high-resolution bathymetry and compaction trends constitutes a new approach for iteratively building a 3D geomechanical model. Effective stress (as a function of x, y and depth) is derived by applying Terzaghi's principle within an integration (along depth) involving the model bulk and fluid densities and the vertical component of gravity (all of which may vary with x, y and depth, using more refined models).

Carbonate and mudrock rock physics models, believed to be appropriate for Neogene sediments along much of the NW Shelf of Australia were derived from abundant core and wireline data acquired during the recent IODP Expedition 356. These models provide the necessary link between effective stress and P-wave velocity with Backus averaging handling the 'seismic scale' mixing of different lithologies expected in the Kraken 3D area.

Kirchhoff prestack depth migration was revisited from archived preprocessed gathers using the geomechanical model to initiate tomography. Heavy smoothing of velocities was imposed where sequence stratigraphic interpretation suggests only distal mudstone facies. Tomography in shallower layers was then revisited to restore geologically plausible depth structures and deliver a clear improvement in imaging relative to previous processing efforts.

1530–1710
TUESDAY 20 FEBRUARY 2018

7D GEOCHEMISTRY

A NEW BLASTHOLE XRF PROBE FOR MINING GRADE CONTROL

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Mining grade control is often based on geochemical sampling of blast cones. Limitations of this method include; a single assay result representing the entire length of the hole, the requirement of an on-site lab to meet turn-around times, bias generated by sampling of the blast cones and the risk of physical injury during sampling.

A new 125 mm diameter XRF logging probe has been designed specifically for providing chemical assays by wireline logging. This tool will provide a continuous assay log down the length of the blasthole, providing a more representative sampling of the entire hole as well as providing the opportunity for composite sampling over different section of the hole, e.g. to provide more detailed grade control to support selective mining as several flitches within an open-pit bench. Once the system is calibrated, results can be delivered as soon as logging is complete.

This paper presents the results of a series of bench tests demonstrating the accuracy and precision of the prototype BHXRF probe as a grade control tool for different types of bulk commodity or base metal deposits.

CASSITERITE AND RUTILE AS INDICATOR MINERALS FOR EXPLORING THE VMS SYSTEM, GOLDEN GROVE, WESTERN AUSTRALIA

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Cassiterite and rutile strongly resist physical and chemical weathering. These minerals are abundant in a near-surface silcrete duricrust capping a deeply weathered profile over the Scuddles Cu–Zn–Pb VMS deposit, Golden Grove, Western Australia. Silcrete consists mainly of massive microcrystalline quartz at depth grading upward into silicified, collapse breccia. Silcrete changes laterally into kaolinitic saprolite and both form a shallow leached zone (<40 m) over supergene Cu–Zn sulphide and oxides zones at depth.

Strongly acidic and highly saline fluids, generated by oxidation of massive sulphides, caused weathering of labile minerals, removal of clays and leaching of alkali, alkaline earth and transition (e.g. Fe, Mn, V, Ni, Co, Cu, Zn) elements, followed by collapse and residual concentration of resistate minerals. Pyrite, chalcopyrite, sphalerite, galena and argentite in the VMS are preserved as inclusions in cassiterite, rutile and quartz in silcrete. Supergene nanocrystalline Au (up to 35 ppm) and Ag (up to 1100 ppm) halides occur as a cavity-filling cement and postdates silica cementation.

After residual concentration in silcrete, cassiterite, rutile and quartz are intensely corroded releasing Sn, Ti, Pb, Sb, Bi, W, Mo and Te. Subsequently, these elements form a cement of complex mineral paragenesis and variable chemical compositions corroding Ag halides. These elements together with Au and Ag are enriched in silcrete forming a narrow halo delineating the underlying Scuddles VMS system.

Discovering mineralised silcrete over the Scuddles VHMS deposit has significant implications for exploration, not only in Australia, but also in regolith-dominated terrains with similar weathering histories elsewhere in the world.

CAN GEOPHYSICS AND GEOCHEMISTRY COMBINE TO DETECT MINERALISATION UNDER TRANSPORTED COVER?

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The oxidation of Fe-containing sulfide mineralisation leads to the development of natural galvanic cells that are characterised by a reduced acid chimney above the mineralisation itself and pH-redox controlled chemical haloes surrounding the chimney and may extend through overlying transported regolith cover of varying thicknesses and composition. Acid reduced chimneys also alter regolith mineralogy (changes to clays, loss of carbonates), which may alter geophysical characteristics such as electrical conductivity (EC). This paper reviews trace element geochemical and EC geophysical mapping over porphyry style Au–Mo–Cu mineralisation at Mandamah (NSW) and MVT Pb–Zn mineralisation at Tappeh Sorkh (Iran). At Mandamah, mineralisation is buried under 50 m of alluvium and a further 30 m of *in situ* regolith. The main mineralised zones are characterised by low EC in the upper 6 m of the regolith profile that can be related to changes in clay mineralogy and the destruction of carbonates caused by the acid chimney. These patterns are variably reflected in pH and the distribution of selectively-extracted Ca, Mg, S, Ba and REE in the upper part of the transported regolith profile, but generally not in the elements of economic interest (Au, Cu or Mo). At Tappeh Sorkh mineralisation is covered by 80 m of dolomitic sedimentary rocks and thin alluvium. There is an increase in EC above mineralisation and adjacent low EC values. The combined geochemical and geophysical approach provides a new approach to exploration in large areas with economically prospective geology but where mineralisation is buried by rock or transported regolith cover.

FIELD ANALYSIS OF LOW PPB GOLD USING PXRF AND NEW DETECTORE TECHNOLOGY

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The ability to analyse gold in the field at meaningful concentration levels for mineral exploration, and in a practical manner, has not been achievable. Portable X-Ray Fluorescence (pXRF) was a game changer for explorers when it became available about a decade ago. However, whereas pXRF can analyse for metals such as Cu, Zn, As and Fe at concentration levels relevant to mineral exploration, it can only reasonably analyse for gold above 10 ppm and only then when interfering elements are absent. Here we present new patented detectORE technology, developed by CSIRO, that can analyse gold using a pXRF at four orders of magnitude lower, at 1–10 ppb concentrations, which will revolutionise world gold exploration. The method has been tested against certified reference materials and whilst not a 'total' gold method like fire assay or neutron activation analysis, it provides the mineral explorer with crucial information in the field. Having data available during the execution of a soil sampling or drilling program allows the geologist to make decisions on where to sample next 'on-the-fly'. For example, adjusting drilling strategy and quickly defining the extent of the mineralisation. Currently, mineral explorers may have to wait weeks or months before the results of the gold analysis are returned from the analytical laboratory, and by this time the drill campaign is over, possibly for another year. Medium to small exploration companies can ill afford to wait that long in the current financial climate.

1530–1710
TUESDAY 20 FEBRUARY 2018

7E BRINE DEPOSITS

LITHIUM: FUNDAMENTAL SUPPLY/DEMAND, THE LITHIUM BRINES OF SOUTH AMERICA AND EXPLORATION/DEVELOPMENT METHODOLOGIES

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Demand for electric vehicles has surprised to the upside in the past year with a widening realisation of a significant shortfall in supply of lithium for lithium ion batteries from both hard rock and brine sources. South American lithium brines contribute approximately 50% of global lithium supply but new supply developments are choked in the short to medium time due to development timelines and regulatory restrictions. Current exploration and development methodologies of lithium brines are reviewed with the latest extraction techniques summarised.

EVALUATING BRINE DEPOSITS USING BOREHOLE MAGNETIC RESONANCE.

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Brine mining is an important source of elements such as potassium, iodine, lithium, and bromine that occur in solution in groundwater, typically in shallow brines occurring beneath saline or dry lakes or in deep brines in sedimentary basins. Where feasible, brine mining is an attractive alternative to conventional mining due to lower surface and environmental impact and lower OPEX than conventional mining operations.

As with any resource, evaluating brine deposits requires developing an understanding of how much resource is present and how it can be most economically produced. How much resource is present is a function of the bulk aquifer volume, the specific yield, and the brine composition, while the primary subsurface control on economic production is hydraulic conductivity, which dictates the rate at which the brine can be produced to surface. Specific yield and hydraulic conductivity are analogous to the free fluid volume and permeability quantities that are of interest in oil and gas resource assessment.

Borehole magnetic resonance has been applied in the oil and gas industry for the evaluation of bound and free fluid volumes and

permeability for over 20 years. These same methodologies are equally applicable in the evaluation of brine deposits, however the hypersaline brines that are targets for commercial development cause highly conductive borehole environments that can be extremely challenging for magnetic resonance measurements. Nevertheless, use of borehole magnetic resonance measurements to help evaluate a sulphate of potash brine deposit currently under assessment shows that such measurements can be employed successfully in these environments.

1530–1710 TUESDAY 20 FEBRUARY 2018

7F NEW AIRBORNE EM TECHNIQUES

SUB-AUDIO MAGNETICS (SAM) – GROUND-BASED AND UAV-BORNE FLEM TRIALS AT THE FORRESTANIA EM TEST RANGE

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Sub-Audio Magnetics (SAM) is a rapid sampling survey technique capable of simultaneous acquisition of data related to the magnetic and electrical properties of the earth. Based on Total B-field Cs vapour sensors, SAM surveys have historically focused on the acquisition of high-resolution Magnetometric Resistivity (MMR) and Total Magnetic Intensity (TMI) data.

Recent developments in SAM receiver instrumentation, data processing and high power transmitter technology have now made SAM Fixed Loop EM (FLEM) surveys possible due to the exceptionally high data quality now being achieved.

SAM data are acquired from a moving platform which makes the technique amenable to applications ranging from ultra-detailed, man-carried or vehicle-towed ground surveys to large-scale Helicopter-borne acquisition. Because the instrumentation is light-weight, it may also be deployed from a remote-controlled or autonomous, unmanned aerial vehicle (UAV) or drone.

This paper describes ground-based and UAV-borne SAM FLEM trials conducted over the Forrestania EM Test Range in Western Australia and compares the results with conventionally-acquired (stationary) SAMSON surveys. The trials have demonstrated that SAM FLEM surveys are able to detect high conductance ore bodies at significant depth from a moving survey platform.

In either ground or UAV mode of operation, the SAM technique is shown to be a significant advance towards reducing the cost of deep exploration for high conductance orebodies.

CGG'S NEW HELITEM C SYSTEMS

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Recent development and re-design of the Helitem helicopter time domain system have resulted in the release of the Helitem$_{30C}$ and Helitem$_{35C}$ systems. This paper describes the design path of these two systems and provides field examples highlighting the major design features.

The Helitem$_{30C}$ is an all-around system designed to be applicable to the majority of TEM surveys. The system utilises a 30 m diameter transmitter loop with a concentric receiver geometry.

The Helitem$_{35C}$ is a high specification system designed to provide the highest Tx power, the lowest base frequency and the lowest noise performance. A 35 m diameter transmitter loop is used, with transmitter moment up to 1.3 MAm^2. Pulse width is configurable, from 4 ms (for resistive/small features) to 10 ms (exploring under conductive cover). Helitem$_{35C}$ employs concentric receiver geometry with a re-designed suspension system which significantly reduces coil motion, allowing it to operate at base frequencies as low as 12.5/15 Hz with no increase in motion noise. 12.5 Hz base frequency provides a measuring time of over 30 ms, which is an important factor for exploring under conductive cover.

To illustrate the design changes, we provide data examples from 25 Hz surveys in Tasmania, 12.5 Hz operation in Western Australia, and geologic mapping for gold exploration from a resistive area.

PASSIVE EM PROCESSING OF MEGATEM AND HELITEM DATA

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The recording of raw or streaming data, as done by CGG during MEGATEM and HELITEM surveys, allows for the extraction of passive EM responses, inadvertently recorded during AEM surveys. These include powerline responses in data sets acquired in the vicinity of strong powerlines, VLF responses in data sets recorded with sufficiently high sampling frequencies and potentially AFMAG responses in the frequency range 25–600 Hz.

The recording of the three-component AEM data allows for the vector processing of these passive EM responses, including the derivation and modeling of the tipper data. Conductivity information can be derived from the tipper data with an apparent conductivity transformation and, more rigorously, with 2D and 3D inversions that take into account the terrain's topography.

The extraction of passive EM responses is demonstrated on a number of data sets. A powerline apparent-conductivity grid, derived from a MEGATEM survey near Timmins, Canada, indicates conductivity structures not evident in the corresponding active-source EM data. VLF responses derived from various HELITEM and MEGATEM data sets, show a strong correlation to topography, but were successfully modeled with 2D and 3D inversions. The derived shallow conductivity structures confirm

and complement the information extracted from the active-source EM data.

1530–1710
TUESDAY 20 FEBRUARY 2018

7G REGIONAL MAPPING METHODS

CHARACTERISING THE SUBSURFACE ARCHITECTURE AND STRATIGRAPHY OF THE MCARTHUR GROUP THROUGH INTEGRATED AIRBORNE EM AND GRAVITY INVERSION

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The Caranbirini sediment-hosted Zn-Pb-Ag prospect is located to west of the Emu Fault, ~20 km north of McArthur River Mine (formally HYC), within the Batten Fault Zone of the McArthur Basin (Northern Territory). The Caranbirini area exposes stratigraphy from McArthur Group and shows some structural complexity with post-depositional folding and faulting. In order to better characterise the subsurface basin architecture we combine structural, sedimentological, and stratigraphic interpretations with 3D gravity inversion, and a 1D airborne electromagnetic inversion. Results are integrated to build a 3D model of the subsurface basin architecture, and identify prospective stratigraphy such as the Barney Creek Formation. 3D gravity inversions were performed using a preliminary 3D geological model of the project area as a reference model for a constrained property inversion. The gravity inversion identified an anomalous density zone immediately west of the Emu Fault. Interpretation of the inverted AEM data provided stratigraphic constraint for the geological model by defining the depth and geometry of the Barney Creek Formation. They also indicated the presence of several N–S trending faults to the west of the Emu Fault coincident with the western boundary of the anomalous density zone. The interpretation suggests that the depth to the Barney Creek Formation increases westwards of the Emu Fault. We interpret the increase in depth to the Barney Creek Formation, in combination with the zone of increased density as a fault-bounded sub-basin, bounded in the west by a paleo-high. Recognition of the sub-basin and controlling faults has implications for targeting Zn–Pb–Ag mineralisation.

SELF ORGANISING MAPS - A CASE STUDY OF BROKEN HILL

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'Self-organising maps' is a type of unsupervised learning technique for multivariate data. It runs through as many layers of data as you can provide it with and finds correlations between them. This means the end users sole responsibility is to evaluate the cause of the correlations. Broken Hill, thanks to the Broken Hill Exploration Initiative, has a data density which is relatively unparalleled. However, thanks to the rising quality of remote sensing, we can expect increasingly high density data sites within Australia and globally. SOM is used to effectively evaluate this very rich data set.

The goals of the project were to develop a workflow that simplified and assisted with data integration and interpretation and then to integrate this software with commercially available packages and become part of a standard workflow. The SOM toolbox creates a SOM domain representation of how component clusters correlate. It DOES NOT give any spatial information. Our work takes the SOM result and translates it back into the spatial domain. It is important to note that none of the results we developed use geological unit maps. Stratigraphic maps were only utilised for remapping individual units, and regolith data was intentionally left out to demonstrate the effectiveness of SOM. Spatial Structures and other regions arise naturally out of the data provided to the SOM.

We present the workflow and MATLAB program we developed to create these spatial maps of correlations indicated by a standard SOM map. Some features such as the Granitic intrusives, unmapped features in the Adelaidean and the high contrasting Silver King Formation (mineralisation zone), are discussed. An emphasis is placed on how SOM works and finds correlations.

This work was submitted for consideration to the Frank Arnott Award.

THE UTILITY OF MACHINE LEARNING IN IDENTIFICATION OF KEY GEOPHYSICAL AND GEOCHEMICAL DATASETS: A CASE STUDY IN LITHOLOGICAL MAPPING IN THE CENTRAL AFRICAN COPPER BELT

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Random Forests, a supervised machine learning algorithm, provides a robust, data driven means of predicting lithology from geophysical, geochemical and remote sensing data. As an essential part of input selection, datasets are ranked in order of importance to the classification outcome. Those ranked most important provide, on average, the most decisive split between lithological classes. These rankings provide explorers with an additional line of reasoning to complement conventional, geophysical and geochemical interpretation workflows. The approach shows potential to directly aid in identifying important criteria for distinguishing geological map units during early stage exploration. Subsequently, this can assist in directing expenditure towards the acquisition and advancements datasets which will be the most productive for mapping.

In this case study, we use Random Forests to classify the lithology of a project in the Central African Copper-Belt, Zambia. The project area boasts extensive magnetic, radiometric, electromagnetic and multi-element geochemical coverage but only sparse geological observations. Under various training data paradigms, Random Forests produced a series of varying but closely related lithological maps. In each case, variable ranking

highlighted those datasets which were of greatest importance to the result. Both geophysical and geochemical datasets were well represented in the highest ranking variables, re-enforcing the importance of access to both data types. Further analysis showed that in many cases, the importance of high ranking datasets had a plausible geological explanation, often consistent with conventional interpretation. In other cases, attention was drawn to datasets that may not have previously been considered to be of interest.

TERRAIN CORRECTION CORRECTION TASMANIA – RESULTS AND IMPLICATIONS

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As Tasmania has the greatest topographic variation of any Australian continental jurisdiction, the terrain correction (TC) is a major component of complete Bouguer anomaly reduction for the State gravity database. TC values >1 mGal are not uncommon, and may exceed 30 mGal, readily swamping anomalies of exploration interest. Accurate determination of the terrain effect is therefore critical.

Most corrections in the Tasmanian database were calculated manually, to 22 km radius. Availability of high resolution elevation models, coupled with high computing capacity, allows revision of these. An earlier pilot project on portions of western Tasmania indicated that the older TC values may be substantial underestimates. In some areas, automatic corrections (to 167 km radius) exceed the former by >5 mGal. The pilot also demonstrated that 25-m. DEMs, currently the best resolution available for the entire State, deliver acceptably low loss of TC accuracy in comparison to 1-m. DTMs from LiDAR.

This paper presents results from the complete statewide TC revision. To enable this, an improved, 'bare earth' version of the State 25-m. DEM was produced. This was achieved by incorporation of a high quality subset of the State survey control points, combination with bathymetry from Tasmania's extensive larger lakes and hydroelectric impoundments, and extension via near-shore marine research data to merge with national bathymetric data. The DTM was also improved in coastal areas by inclusion of low-water-mark mapping together with tidal range information.

Areas of the most substantial TC changes are highlighted, and possible geological and exploration implications examined.

1530–1710
TUESDAY 20 FEBRUARY 2018

7H INNOVATION

LOW NOISE, MULTICHANNEL SURFACE NMR RECEIVER SYSTEM WITH WIRELESS CONNECTIONS TO RECEIVER COILS

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Surface NMR is often considered a promising tool in groundwater measurements due to its unique direct sensitivity to subsurface water and its ability to provide information on the pore space in which the water is situated. The surface NMR method currently suffers from a number of drawbacks limiting its widespread applicability. Among these drawbacks are a low signal to noise ratio limiting the use of the method in many places of interest and a low production rate, which makes the method costly in field campaigns. There is thus a need for new research on instrumentation further advancing the technology. We report on the development of a new multichannel, low noise surface NMR receiver system with wireless connections to noise reference receiver coils. Due to the wireless operation, noise reference receiver coils can be located near particular noise sources and remain there as the NMR transmitter and receiver coil is moved between different measurement sites improving both noise reduction and field methodology. The receiver system works as a completely independent add-on to existing transmitter systems and consists of a number of independently operated data acquisition boxes connected with WiFi and synchronised by GPS. The internal electronic noise level of the system is 1.2 nV/sqrt(Hz). The timing jitter between data acquired in different boxes is less than 100 ns.

ECLOUD – MAGNETOTELLURIC WEBAPP

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Geophysical web applications are highly underrated. There are many potential benefits for transitioning to a cloud based web applications, including compatibility improvement, low on-going operating costs and better access to existing third-party code and tools for facilitating rapid development. For users, time spent on installation, general IT maintenance such license management and upgrading is minimised.

While web applications for business style applications are deeply established, scientific applications on the web are only just emerging. This research builds upon our previous feasibility study (Pethick and Harris, 2015), which was the development of a 1D MT web application. This is to be redeveloped into a commercial grade cloud hosted geophysical inversion web app that can cooperatively invert seismic and magnetotelluric (MT) data. Our software, ECloud, is designed to be user friendly where geoscientists and drillers can upload MT field data

directly from their laptop, tablet or mobile to obtain subsurface geo-electrical distributions quickly with minimal input. This application is designed to be scalable, suiting cloud environments and is currently hosted on an Amazon EC2 instance. The preconceived notion that web applications are slow will be challenged. The purposefully designed MT algorithm and software structure will hopefully result in lower computation times while minimising restrictions based on hardware requirements (i.e., primary memory).

GROUNDWATER ASSESSMENT IN A COAL MEASURES SEQUENCE USING BOREHOLE MAGNETIC RESONANCE

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Hydraulic behaviour of an aquifer is defined in terms of the volumes of water present, both producible and not (specific yield and specific retention), and the productivity of the water (hydraulic conductivity). These parameters are typically evaluated using pumping tests, which provide zonal average properties, or more rarely on core samples, which provide discrete point measurements. Both methods can be costly and time-consuming, potentially limiting the amount of characterisation that can be conducted on a given project, and a significant measurement scale difference exists between the two.

Borehole magnetic resonance has been applied in the oil and gas industry for the evaluation of bound and free fluid volumes, analogous to specific retention and specific yield, and permeability, analogous to hydraulic conductivity, for over twenty years. These quantities are evaluated continuously, allowing for cost-effective characterisation, and at a measurement scale that is intermediate between that of core and pumping tests, providing a convenient framework for the integration of all measurements.

The role of borehole magnetic resonance measurements in hydrogeological characterisation is illustrated as part of a larger hydrogeological study of a coal measures unit and associated overburden. Borehole magnetic resonance has been used for aquifer and aquitard identification, and to provide continuous estimates of hydraulic properties. These results have been compared and reconciled with pumping test and core data, considering the scale differences between measurements. Finally, an integrated hydrogeological description of the target rock units has been developed.

GEOLOGICALLY-CONSTRAINED INTERPRETATION OF AIRBORNE ELECTROMAGNETIC DATA FOR DEFINITION OF PROSPECTIVE GROUNDWATER RESOURCES, ALBANY HINTERLAND, WESTERN AUSTRALIA

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A TEMPEST airborne electromagnetic survey was flown in the Albany Hinterland with the objective of determining likely palaeochannel locations for future groundwater exploration. The basement in the survey area is the Proterozoic Nornalup Complex, which is overlain by Tertiary-Eocene sediments, including the Werillup Formation and Pallinup Siltstone. These units are overlain by Quaternary sediments of thickness 10–70 m. The maximum thickness of cover materials overlying basement is ~100 m. The main aquifers in the area are Werillup Formation sands within palaeochannels incised into the basement.

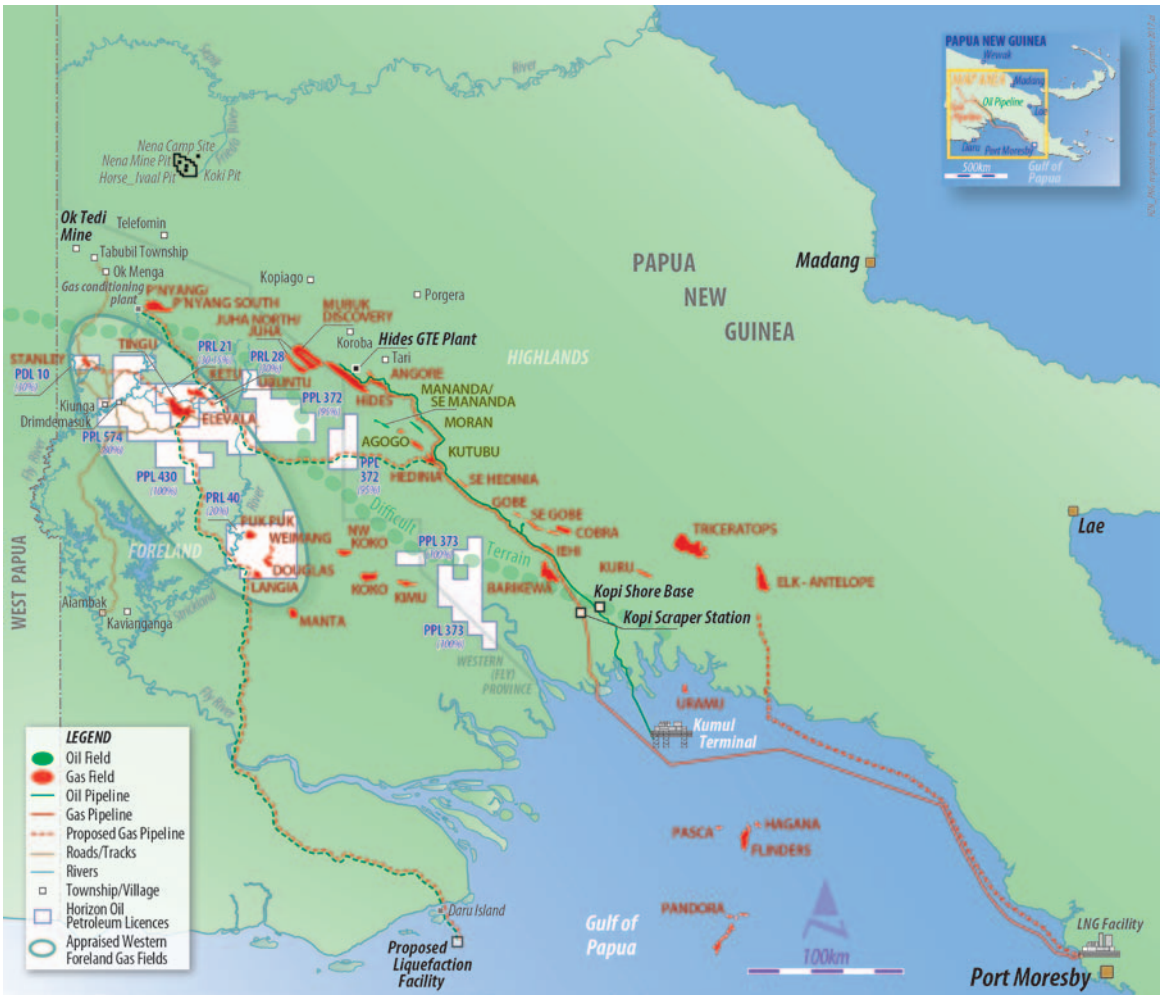
The conductivity derived from the TEMPEST data shows a layer of moderate electrical conductivity (50–150+ mS/m), which correlates well with clayey units within the Werillup Formation, and possibly also the weathered upper part of the Proterozoic bedrock. Bedrock conductivities are typically low (average ~1.2 mS/m). The strong electrical contrast between the Werillup Formation and the bedrock allowed depth to Proterozoic basement to be interpreted from the TEMPEST data. This was done by conventional unconstrained layered-earth inversion followed by manual interpretation of the depth to bedrock on each survey line. The interpreted bedrock depths were used to construct a triangulated surface representing base of cover. Geologically-constrained inversion of the TEMPEST data was then undertaken to refine the preliminary depth to basement model. Geological constraints on the model were provided by drillhole basement pierce points and outcrop. A large number of drillholes which did not reach bedrock were also used. The inversion was constrained to place the final bedrock surface below the ends of these drillholes.

The geologically-constrained inversion and subsequent synthesised interpretation identified a number of bedrock lows which have been confirmed by drilling to correspond to palaeochannels, and has defined four main groundwater resource areas. The results of the interpretation have formed the framework for the Albany Hinterland Prospective Groundwater map (Ryan *et al*., 2016).

Horizon Oil - focused on the future

The sharp and sustained fall in prices experienced since 2014 has been the defining feature of the oil and gas industry in recent times. Globally, many projects have been deferred or cancelled, the workforce has been in decline and there have been substantial reductions in exploration expenditure around the world. While Horizon Oil is not immune to the challenges facing the industry generally, the Australian based, ASX-listed upstream oil and gas company continues to see attractive opportunities in Papua New Guinea and is pushing ahead with plans to commercialise its gas-condensate resources in PNG's remote, but highly prospective, Western Province.

It is noteworthy that despite the difficult market conditions, Papua New Guinea continues to attract strong competitive interest from major investors. This interest has been demonstrated by the entry of Total S.A. into Elk/Antelope and more recently, by ExxonMobil's US$2.5 billion purchase of InterOil Corporation. Furthermore, substantial expenditure on exploration and appraisal drilling continues to be incurred by large companies (including Oil Search and Santos) in close proximity to Horizon Oil's Licence areas. This investment activity highlights the stability and attractiveness of PNG as an oil and gas investment destination. It also underlines the value of Horizon Oil's material PNG asset portfolio; a commanding acreage position in the northern forelands of Western Province which includes a Petroleum Development Licence over the Stanley Field (PDL 10), and Petroleum Retention Licences over the Elevala and Ketu Fields (PRL 21), the Puk Puk and Douglas Fields (PRL 40) and the Ubuntu Field (PRL 28).



Gas commercialisation pathways emerging

Horizon Oil's primary focus is to develop its Western Province resources and work completed to date has identified a number of promising gas commercialisation pathways. PRL 21, which contains the Elevala and Ketu fields, is of particular importance in this context. The Elevala and Ketu gas-condensate fields contain a combined independently certified gross contingent resource (2C) of 1.4 trillion cubic feet of gas and 56 million barrels of condensate, forming the cornerstone volume needed for Horizon Oil's gas commercialisation efforts. These gas-condensate fields were originally discovered in the early 1990s and are located some 60 km east of the Western Province port town of Kiunga. A comprehensive appraisal program, consisting of 3 appraisal wells and 205 km of 2D seismic, was completed between 2011 and 2013 with the results of that appraisal program and subsequent analysis confirming the commerciality of the Elevala and Ketu fields.

The high ratio of condensate to gas found in both the Elevala and Ketu fields initially supported a two phase development plan aimed initially at gas recycling and condensate recovery in the first phase, with gas commercialisation options to be evaluated and matured in a subsequent second phase of the development. A Petroleum Development Licence application was submitted to the PNG Government on that basis in March 2014, targeting initial condensate production of 10,000 to 12,000 barrels per day. Pleasingly, there has been significant progress made with the regulatory approval process, including receipt of formal approval by the PNG Conservation and Environment Protection Authority of the Elevala development Environmental Impact Statement.

In response to the recent commodity price market, when oil prices were sitting below US$50/barrel, the attention of Horizon Oil and its PRL 21 joint venture partners turned to combining both phases by accelerating the gas commercialisation phase of the overall development plan. Horizon Oil's proposed Western LNG project seeks to aggregate these gas fields to develop 2.0 to 2.5 trillion cubic feet of gas and 60 to 70 million barrels of condensate. The aim is to export the gas and condensate via pipeline and an offshore LNG facility which will have a capacity of around 1.5 million tonnes per annum.

Crucially, the resources in Western LNG are held by only 6 participants, with almost 70% concentrated in the hands of Horizon Oil and the Spanish major Repsol. This consolidation of ownership is important as it will make the process of development planning and aggregation simpler than with a widely dispersed ownership group.

The LNG market is becoming rapidly aware of the potential of smaller LNG developments, with strong demand growth for LNG in emerging South East Asian economies, particularly in relation to dispersed power generation, and this is largely being driven by new entrants who want greater flexibility of supply. PNG is somewhere of a sweet spot from which to meet those needs.

Western LNG is targeting start up in the early 2020s when it is anticipated that the South East Asian markets will be undersupplied with LNG. While focusing on export markets a key component of the development criteria is making sure that the development plan maximises the potential for domestic PNG market access for gas and LPG. The design concept provides multiple gas offtake points for local industrial consumers and power generation.

Preliminary economics are attractive and Western LNG, if successful, will be expected to generate around US$1 billion a year for 20 years or more. The project is in pre-Front End Engineering and Design now, Horizon Oil anticipates proceeding into Front End Engineering and Design in 2018, with a Final Investment Decision scheduled for 2019.

Although focusing on export opportunities, Horizon Oil is a strong supporter of proposals aimed at developing PNG's resources for domestic consumption and the Company is actively pursuing domestic market opportunities. PNG's mineral resource industry provides substantial opportunities to substitute clean natural gas for diesel or heavy fuel oil-fired power, adding value not only to mining operations but also to power intensive mineral processing and refining within PNG. Horizon Oil's gas resources, along with the significant upside potential provided by nearby exploration prospects continue to represent a significant commercial opportunity for PNG and the Western Province to establish and develop infrastructure, industrial activity, employment and export revenue based on a secure and long-term gas and fuel supply resource.

Stakeholder engagement - an ongoing priority

While focused on the technical task of planning and designing a major gas project, Horizon Oil remains cognisant of the broader social context in which it operates in PNG. Community expectations do not change with a rise or fall in the price of oil or gas and like many resource developers, Horizon Oil expends considerable effort on stakeholder engagement. Many of Horizon Oil's project area communities are located in remote, difficult to reach areas. A core tenet of Horizon Oil's stakeholder engagement activity is the maintenance of 'face to face' contact, essential for building positive relationships. This work is primarily led by the Community Affairs team who make

regular visits to project area villages, often staying overnight, to conduct formal and informal information sessions. These village visits are fundamental and provide community members with an important opportunity to ask questions, share their views or offer insights into Horizon Oil's activities.

Although the current commodity price environment has caused Horizon Oil, like all petroleum companies, to cut costs, this does not extend to our commitment to community support and in this regard the Company has maintained our partnerships with Australian Doctors International and Mercy Works. ADI is a not-for-profit, non-government development aid organisation which has been focused on strengthening primary health care services in rural and remote communities in PNG since 2002, and Mercy Works provide maternal health focused training services to regional health centres and rural aid posts, training programs for women and low cost child care for working mums along with workshops in rural communities aimed at minimising violence in families and communities. The partnerships see Horizon Oil allocate A$100,000 (PGK200,000) annually to support the deployment of voluntary medical practitioners in the Western Province of PNG. Two ADI doctors have been deployed since 2016 and the partnership is on track to deliver a broad program of clinical consultation with structured and unstructured in-service training to health workers in remote Western Province communities.

There is no doubt that the last few years have been challenging ones for the oil and gas industry. Nevertheless, Horizon Oil continues to see robust opportunities in PNG and remains firmly focused on pursuing those opportunities with the intention of bringing its Western Province resources to production.

Wednesday 21 February 2018

0830–1010
WEDNESDAY 21 FEBRUARY 2018

8A NEW TECHNOLOGY – SEISMIC

BROADBAND LEAST-SQUARES WAVE-EQUATION MIGRATION

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We introduce an efficient iterative Least-Squares Wave–Equation Migration (LS–WEM) solution for broadband imaging. Least-Squares Migration (LSM) solutions are designed to produce images of the subsurface corrected for wavefield distortions caused by acquisition and propagation effects. They implicitly solve for the earth reflectivity by means of data residual reduction in an iterative fashion, which usually demands intensive computation. The LS–WEM is implemented using an acoustic anisotropic one-way wave-equation wavefield propagator that is able to fully utilise both the broader seismic bandwidth and the high-resolution velocity information from Full Waveform Inversion (FWI). Our implementation combines the one-way extrapolator with fast linear inversion solvers into an efficient migration inversion system. Application to the 2D Sigsbee2b synthetic model improves the sub-salt illumination by balancing the image amplitudes and reducing the effects of the shadow zones, enhances temporal resolution by broadening the frequency spectrum, balances the wavenumber content and improves images of faults and dipping salt flanks. In addition, LS–WEM converges rapidly to the true solution, reducing the data residuals by 90% in only four iterations. Application to real 3D datasets from the Gulf of Mexico and the North Sea demonstrates high-resolution imaging with reduced acquisition footprint effects, improved spatial frequency content, and better structural imaging at all depths.

METHODS FOR REDUCING UNWANTED NOISE (AND INCREASING SIGNAL) IN PASSIVE SEISMIC SURVEYS

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Passive seismic surveys are becoming of increasing interest for characterising the near surface, in particular the depth of cover. For passive seismic acquisition ambient noise is both signal and noise. The 'signal' component is generally considered to be energy resulting from distant sources (storms, tides etc.) while the 'noise' component is a result of near sources (vehicles, vegetation movement etc.). For surveys to be successful we clearly need to maximise the former while minimising the latter. We cannot directly increase the amount of source energy so instead we need to ensure that we enhance the recording of the signal while minimising unwanted noise. In this paper we describe how the positioning and coupling of seismic sensors can be optimised to maximise the signal-to-noise ratio of passive seismic data.

QUANTITATIVE INTERPRETATION: USE OF SEISMIC INVERSION DATA TO DIRECTLY ESTIMATE HYDROCARBON RESERVES AND RESOURCES

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A quantitative interpretation workflow utilising AVO inversion based lithology prediction data was developed to directly assess reserves and resources for an LNG development project in the Carnarvon Basin. The study area is covered by modern MAZ PSDM 3D seismic data using broadband acquisition and processing techniques, calibrated by numerous well intersections of the Triassic Mungaroo Formation reservoirs.

Interpretation of the fluvio-deltaic reservoir bodies can be somewhat interpretive using 'traditional' workflows. By interpreting chrono-stratigraphic events tied to well-based biostratigraphy and then using the lithology prediction volumes, the interpretation of reservoir bodies becomes more objective.

Seismic inversion data are typically used to qualitatively guide resource assessments, through amplitude mapping or use in static and dynamic modelling. In this case study, the inversion based prediction volumes are used to extract P90, P50 and P10 sand geobodies which are directly input into probabilistic reserve and resource assessments. The workflow is applied to discovered, developed, undeveloped and prospective reservoirs.

Geobody extraction required the PSDM depth data to be accurately calibrated to wells. A calibrated velocity model was built by perturbing the imaging velocities in a 3D model to tie the chronostratigraphic events associated with all the reservoir intervals. Fluid contacts derived from wells were used to provide a depth cut-off to the geobody extractions.

The resulting reserve and resource assessments from this workflow show an excellent match with previous assessments including static and dynamic modelling methods. The geobodies also identified previously unrecognised channel sands not easily interpreted on full and angle stack data.

SOLID SUBSTITUTION: THEORY VERSUS EXPERIMENT

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Gassmann fluid substitution is widely used in geophysical practice. In the last few years a topic of fluid/solid substitution has emerged, where the substances filling the pore space can be solids, fluids, or visco-elastic materials such as heavy oils. Solid substitution cannot be accomplished with the Gassmann theory because the finite rigidity of the pore fill (either solid or viscoelastic) prevents pressure communication throughout the pore space, which is a key assumption of the Gassmann theory. In this paper we explore applicability of solid substation techniques by using a sandstone saturated with a solid substance, Octadecane, a hydrocarbon with a melting point of 28°C, making it convenient to use in the lab in both solid and fluid

form. Our approach is to measure a dry sandstone sample, then saturate it with liquid Octadecane at 35°C, measure, cool it to 20–25°C and measure again. The dry properties can be used to obtain parameters necessary for fluid and solid substitution. The results show that moduli of the dry sandstone exhibit significant pressure dependency, which is reduced for the solid filled rock. Also the prediction of the Gasmann theory and Ciz and Shapiro theory underestimate the velocities. This suggests that stiffening occurs due to substantial reduction of compliance of grain contacts by the solid infill. This effect is accounted for by the solid squirt theory. The results give direct evidence of the solid squirt effect and can be used to verify and calibrate theoretical solutions for rocks saturated with solid or viscoelastic substances.

0830–1010
WEDNESDAY 21 FEBRUARY 2018

8B NEW TECHNOLOGY – CO_2

ROCK-PHYSICS BASED TIME-LAPSE INVERSION IN DELIVERY4D: SYNTHETIC FEASIBILITY STUDY FOR CO2CRC OTWAY PROJECT

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Conventional approach to 4D seismic inversion consists of parallel inversions applied to seismic vintages. Only then, the inverted changes of seismic attributes are converted into petrophysical properties using rock physics. This paper develops a robust approach to 4D seismic inversion based on a Bayesian approach along with rock physics constraints. This means that observed time-lapse seismic response along with the baseline amplitudes are inverted directly into rock properties via pre-defined relations to the seismic properties. To this end, we extend the functional of Delivery - an open-source stochastic inversion software.

We illustrate efficiency of Delivery4D using synthetic 4D dataset generated for Stage 2C of CO2CRC Otway project, Victoria. Complexity of the synthetic wavefield resembles field data acquired for the Otway project while all unknown sources of noise/uncertainty are excluded and we have 'ground-truth' subsurface properties.

Despite the relatively thin CO_2 plume, the 4D inversion reduced detected time-lapse anomaly to the location that closely corresponds to the actual CO_2 plume. Estimated distributions of the plume characteristics (thickness, saturation and CO_2 mass) are overall similar to the static and dynamic geomodels. However, the values inverted at a particular trace may differ significantly. We attribute these discrepancies to the limited seismic resolution and imperfections of the amplitude-preserved seismic processing.

APPLICATION OF TIME-LAPSE FULL WAVEFORM INVERSION OF VERTICAL SEISMIC PROFILE DATA FOR THE IDENTIFICATION OF CHANGES INTRODUCED BY CO_2 SEQUESTRATION

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Seismic methods are frequently used for the purpose of monitoring of time-lapse changes introduced by CO_2 sequestration. Surface seismic is often considered as the main tool for monitoring. Vertical Seismic Profile (VSP) is occasionally applied as an auxiliary method. Standard VSP data processing workflow does not provide a quantitative estimate of the time-lapse changes in the physical properties. However, full waveform inversion (FWI) may be used for the purpose of quantitative interpretation. Its ability to employ the whole seismic wavefield (including transmitted, reflected and converted waves) for the purpose of building the models of physical properties can be considered one of its main advantages.

We show that time-lapse elastic FWI of single- or multi- offset VSP data is capable of providing quantitative estimates of time-lapse changes in the medium. A feasibility study is carried out on 2D and 3D synthetic datasets created using full-earth models of the CO2CRC Otway CO_2 sequestration site. The inversion workflow obtained from the feasibility study is successfully applied to a field single-offset time-lapse VSP dataset. As a result, FWI provides an image of the time-lapse changes introduced by the injection of supercritical CO_2.

3D VERTICAL SEISMIC PROFILING ACQUIRED USING FIBRE-OPTIC SENSING DAS – RESULTS FROM THE CO2CRC OTWAY PROJECT

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Distributed Acoustic Sensing (DAS) is an optical interferometric method for acquisition of acoustic and seismic signals. It uses laser pulses that travel along the length of the fibre-optic cable and backscatter as they encounter small inconsistencies in the fibre. Impinging seismic waves cause strain on the cable, resulting in differences in phase of the backscattered light. Interest in DAS has increased significantly in the past decade as it is particularly suited for VSP acquisitions, including for permanent reservoir monitoring. Fibre-optic cables can be installed permanently in the well, cemented behind the casing or in the tubing; they offer a relatively cheaper and efficient solution when compared to conventional borehole sensors.

This study is part of the CO2CRC Otway Project. The Otway Project site is located approximately 240 km south-west of Melbourne, Australia. The Stage 2C of the project aims to monitor a small injection (15 kt) of CO2/CH4 gas mixture at a depth of approximately 1500 m (Paaratte Formation). Here, we

show the results of a 3D VSP survey acquired using DAS, as part of the fourth monitoring survey for Stage 2C. We aim to analyse the quality of DAS 3D VSP by establishing levels of signal and noise, as well as investigating directivity patterns of the data. Also, we analyse the feasibility of using DAS for detection of the gas plume.

GEOCHEMISTRY OF STORING CO_2 AND NO_X IN THE DEEP PRECIPICE SANDSTONE

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The Precipice Sandstone in the Surat Basin is being appraised for CO_2 geological storage owing to its high porosity and permeability and expected high injectivity. Generally it is quartz rich with variable kaolinite, however detailed characterisation of core shows that it contains minor to trace amounts of potentially reactive minerals including carbonates, plagioclase, chlorite, and muscovite, increasing towards the overlying Evergreen Formation top seal. The Evergreen Formation is mineralogically more variable with interbedded low porosity and permeability mudstones, fine-grained sandstones, and calcite cemented zones. Recent data from capture technologies has reported that CO_2 from coal combustion will retain NOx impurities in the form of NO. Experiments performed in our laboratory at reservoir conditions show CO_2-NO lowers pH and is more reactive to minerals in the core than pure CO_2. Geochemical modelling will investigate the optimum amount of NO that can enhance long term mineral trapping compared to pure CO_2 injection in the Precipice Sandstone. The optimal CO_2 quality (purity) with respect to groundwater TDS will also be discussed. Our previous work with CO_2 +/– SO_2 and O_2 impurities has shown a mineralogical control on the reactive geochemistry especially in the overlying Evergreen Formation, where calcite cemented zones below the sealing mudstone sections can favourably buffer the acidity generated by the dissolved impure CO_2 stream.

0830–1010
WEDNESDAY 21 FEBRUARY 2018

8C CENTRAL AUSTRALIAN BASINS SYMPOSIUM

EVOLVING EXPLORATION METHODS IN THE HYDROCARBON PLAY WITHIN THE PATCHAWARRA FORMATION ON THE WESTERN FLANK, COOPER BASIN

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The hydrocarbon play in the Patchawarra Formation lies within a Permian age, high latitude, fluvial sand and coal measure system that is some 300 m thick and deposited in the Cooper Basin of Central Australia. Fluvial sand channels, ranging from 1 to 20 m thick, form a conventional reservoir. Seal and source play components are in the inter-bedded overbank, silts, clays and coal seams. The low seismic reflectivity sands combined with the numerous, high seismic reflectivity coals makes standard seismic interpretation difficult. These factors combined with the thin, irregular geometry of the reservoir, make exploring for hydrocarbon traps challenging.

The largest fields in the Western Flank, discovered to date, are considered to have a stratigraphic trap component that is combined with a structural influence. Each field has a single main pay zone located in different clastic package compared to the other fields in the play.

An evolving exploration method is reviewed that uses the coals as local timelines with trap limits defined using structural and stratigraphic indications from the seismic. This method combined with ideas of source and trap has recently proved successful in extending the play.

Examples of some of the hydrocarbon traps and concepts are shown that may help with evolving ideas and future exploration methods in this basin and other basins with similar fluvial plays.

STROMATOLITE CONSTRUCTION, BIOFACIES AND BIOMARKERS IN THE LOWER CAMBRIAN HAWKER GROUP, ARROWIE BASIN, SOUTH AUSTRALIA

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Stromatolites are laminated microbial deposits, normally composed of accretionary layers of cyanobacteria and other (often anoxic) bacteria which form on the sediment-water interface. Stromatolites represent one of the earliest records of life on Earth, dating back at least 3.7 billion years. Stromatolites became extremely diverse and very abundant throughout the Archaean era 4–2.5 billion years ago, eventually causing increasing levels of atmospheric oxygen on Earth, as part of the Great Oxidation Event. The emergence and radiation of bilaterian animals and the development of new and more complex food webs during the early Cambrian coincided with a sharp decline of the abundance of stromatolites – yet they continued to exist in a range of Cambrian carbonate environments. The appearance, environment, and possibly the biogeochemistry, of Cambrian stromatolites appears to have been altered after the evolutionary development of epifaunal grazing bilaterians. We sampled stromatolites from a wide spectrum of carbonate facies in the lower Cambrian Hawker Group in the Ikara-Flinders Ranges, South Australia. The appearance, construction, distribution, and biogeochemistry of stromatolites from different depositional environments, including phosphatic hardgrounds, intertidal shoals and shelf/ramp settings is being described as part of an investigation into their morphological variation and ecological association, aiding in the clarification of specific stromatolitic biofacies, and taxonomic associations. There has been little research on the morphology, architecture, growth, and biogeochemistry of stromatolites of stromatolites in the Arrowie Basin; this study is designed to provide novel data about stromatolite evolution and ecology during a period dominated by the radiation of complex animals.

RESERVOIR MODELLING, STRUCTURAL HISTORY AND VOLUMETRICS OF THE JERBOA AREA, EYRE SUB-BASIN

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The Eyre Sub-basin occurs towards the western end of the Southern Australian rift system that has developed since the Jurassic. Jerboa-1, the only well in the sub-basin, was drilled by Esso in 1980 on a mid-basin high using sparse 2D seismic. Though 'dry', subsequent studies estimate a 15 m palaeo-oil column indicating a working petroleum system with Jurassic source rocks. The Jerboa-1 trap was breached in the Early Cretaceous, however, there is the potential of non-breached traps elsewhere in the sub-basin. Regional interest has led several companies to restart exploration including Santos, Murphy Oil, Chevron, BP and JX Nippon.

The Curtin University petroleum group has an active program of seismic, reservoir characterisation and organic geochemical research. The Jerboa area has been remapped with the latest seismic, well logs and core data to produce 3D models of the basin structure, burial and thermal histories. More detailed 3D reservoir models investigate the facies and trap integrity around the well through time and the results reveal new insights into the petroleum potential of the region.

The 3D modelling allows estimation of volumes in the palaeo-trap and associated traps. The Jerboa structure possibly held >20 million barrels of oil with potential for much larger accumulations. Other potential traps exist down-dip in the sub-basin where trap breaching may be less than on the inter-basin highs. These plays are comparable with East African Rift Systems, where spectacular exploration successes have occurred recently drilling down-dip, after 50 years of unsuccessful drilling on the obvious highs.

TERTIARY DEEP-WATER CORAL SUPPORTS COLD SEEPS IN THE CEDUNA SUB-BASIN

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The analysis of new 3D seismic and the acquisition of unique core data enables an in-depth interpretation of outboard Eocene mounds in the central Ceduna Sub-basin and a more accurate model of their origin.

Seismic attributes and spectral decomposition clearly image the 3D morphology and internal architecture of the mounds and enable building episodes to be defined. Mounds have length of 5-35 km, width of 1–4 km and heights of 50–110 m and developed at water depth 300–600 m. Gravity core of the top of one mound indicates that it consists, at least partly, of corals typical of a deep-water reef. This initial interpretation is based on comparison with modern reef-forming biota, the presence of suspected brachiopods and lack of gastropods.

The underlying faults control the initial localisation of the mounds. These faults were active in the Cretaceous and reactivated in the Tertiary and intersect sequences modelled as oil- and gas-mature.

One main control for deep-water coral is the need for suitable hard substrates for initial attachment. The distribution of the mounds supports a development mechanism that relies on carbonate hardgrounds produced by chemosynthetic communities metabolising nutrients from natural hydrocarbon cold seeps along reactivated faults and segments intersections. A hydrothermal feedstock for these communities is possible but less likely due to the distance to the nearest volcanic bodies. Once the substrates are in place the mounds growth is not directly dependant on ongoing cold seeps and could be as well related to the specifics of hydrodynamics in the areas.

0830–1010
WEDNESDAY 21 FEBRUARY 2018

8D HISTORY

OCEAN AND ATMOSPHERE CHEMISTRY DRIVE CYCLES OF BASIN-HOSTED ORE DEPOSITS THROUGH TIME

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Trace element concentrations in marine pyrite, measured by laser ablation ICP-MS, have opened a new window into deep time ocean chemistry, atmosphere oxygenation and genesis of basin-hosted ore deposits (Large et al., 2014, 2015, 2017). A database of over 5000 marine pyrite trace element analyses has enabled the development of deep time proxies for nutrient supply, productivity, ocean pH and atmosphere oxygenation. These proxies suggest that the Archean ocean was enriched in Fe, Ni, Co, As, Au and Hg compared with modern oceans, probably related to composition of erosive flux from the continents and active seafloor hydrothermal activity. This was also a time for major iron, gold and nickel ore formation in sedimentary and greenstone settings. In the Palaeoproterozoic there was a decrease in Ni, Co, As and Au replaced by increasing Cu, Zn and SO_4^{2-} in the oceans and O_2 in the atmosphere. The first appearance of red beds and evaporates is a response to the rise in O_2 and SO_4, and provided the conditions necessary for sediment-hosted Cu and Pb–Zn–Ag deposits. Through 1700 to 1500 Ma, phosphorous, gold and most other nutrient TE dropped to a minimum in the ocean, possibly related to tectonic stasis and changes in atmosphere O_2 and/or ocean pH. Sediment-hosted Au, orogenic Au and VHMS deposits are virtually absent from this period, whereas mineral systems that required relatively oxidised ore fluids, such as SEDEX Zn-Pb and IOCG became more abundant, due to these changed conditions. All redox sensitive and nutrient TE rose dramatically in concentration at the Proterozoic–Phanerozoic boundary and peaked in the mid to late Cambrian, accompanied by black shale deposition enriched in Mo, Se, Ni, Ag ± Au and PGE. Cyclic variation in nutrient TE increased in frequency through the Phanerozoic on a wavelength of 50 to 100 Ma, compared with 500 to 1000 Ma in the Proterozoic. The more frequent Phanerozoic cycles relate to repeated episodes of continent collision, mountain building and increased erosive flux of TE into the oceans. Ore deposit cycles in the Phanerozoic of SEDEX Zn-Pb, orogenic sediment hosted Au and VHMS have a similar time frame to the tectonic and seawater chemistry cycles.

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QUEST FOR THE HOLY GRAIL; BHP'S GEOPHYSICAL RESEARCH PROGRAM 1985–2005

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Over the period from 1985 to 2005, BHP Minerals carried out three major geophysical research projects that were intended to significantly enhance the ability to find new ore deposits. This involved major activities internally as well as external components that involved complex multi-year programs involving the large expenditure of funds. In all cases, major efforts were made to deploy the outcomes in BHP's exploration programs. While the technologies developed could be considered as successful in having met or exceeded the original development goals, in no case did the outcomes of these efforts contribute materially to the discovery of significant new mineral resources. This suggests that the technical objectives for a new technology were comparatively straight forward to define but the subsequent implementation path, once the technological goals are achieved, were poorly conceived.

BHP's experience is much like the exploration industry as a whole over the same period. While much appears to have been developed that has added significantly to the technical capabilities of the industry, it has been less apparent that these developments have been able to contribute significantly to an improved discovery record.

Considerable effort is now being directed towards bringing new geophysical technologies on in programs such as *Uncover* in Australia and CMIC's *Footprint* in Canada. Past experience suggests, however, that better technology alone can't be expected to achieve the sought after goal of improved discovery success.

TEN YEARS IN THE WILD: THE P223 EXPERIMENT

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The use of open-source codes has become pervasive over the past 20 years but such codes are uncommon in minerals exploration. The P223 series of programs researching forward and inverse modelling of electromagnetic data was supported by CSIRO and six AMIRA consortia over 27 years and produced, amongst others, the codes, Airbeo, LeroiAir and Marco. This project concluded in 2008 and, after a two-year embargo, the code base, consisting of computer programs modelling different approximations of the earth for ground and airborne prospecting systems, was released to the public. Our study examines highlights of the research program and the evolution of some programs of the suite in the 10 years since the program concluded. We ask why codes have not been more widely adopted, and examine the evolution of some of the codes in research, academia and in industry as a guide to parties who would embark on a similar route.

0830–1010
WEDNESDAY 21 FEBRUARY 2018

8E GEOPHYSICAL CASE STUDY

CONSTRAINED 3D MODELLING AND GEOCHEMICAL ANALYSES OF THE HORSESHOE RANGE BIF: TOOLS FOR EVALUATING MAGNETIC SIGNATURES UNDER COVER

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The Horseshoe Range is a banded iron formation (BIF) in the Southern Capricorn Orogen, WA, and is associated with a large linear positive magnetic anomaly. Electron microscope mineralogy identified ubiquitous goethite and magnetite/hematite. This study focussed on measuring the magnetic properties of the rocks at Horseshoe Range in order to accurately predict their geophysical responses when buried beneath cover.

The BIF can be modelled using a single homogenous layer with a susceptibility of 0.8 SI. However, this is not geologically consistent with BIFs which typically display variable iron-oxide mineralogy and associated petrophysical properties.

One way to more accurately model BIFs is to use the first vertical derivative as the model input. Using this approach, a 4 layer model was generated which matched the anomaly to an RMS of ~1%. Modelled susceptibilities ranged from 0.01–0.55 SI which is consistent with the measured properties. However, this model did not take into account the measured high intensity downward magnetisation vectors.

Remanent magnetisation intensities of the rocks were high (up to 1300 A/m) and vectors measured in the rocks were oriented predominately downward which typically result in negative anomalies which is inconsistent with the observed anomaly.

Due to the positive nature of the magnetic anomaly, and the ability to accurately model the response without remanent magnetisation, it appears that the high intensity remanent magnetisations may be volumetrically insignificant and likely limited to the near surface. The remanence may be caused by near surface formation of maghaemite during bushfires and/or induced by lightning strikes.

COMPARING RESPONSES FROM DIFFERENT AEM SYSTEMS AND DERIVED MODELS AT THE SUNNYSIDE NICKEL PROJECT, BOTSWANA

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The Sunnyside nickel deposit in SE Botswana is a shallow Selebi-Phikwe type deposit composed of disseminated, blebby and massive nickel sulphides. It was discovered by Anglo American in the 70s but considered uneconomic to mine. It is associated with pyroxenite and gabbro, and is an extremely complex orebody. Since that time several nickel companies have explored the body further, trying to improve on the size and grade and confirm whether the body extends to depth.

The deposit has been surveyed to date by four different AEM systems, being VTEM, Spectrem, SkyTEM and Xcite. In addition, detailed ground geophysics in the form of moving loop TDEM and AMT has been done. In this paper we present a detailed comparison of the EM data measured by the four systems, and of the models derived through quasi-3D spatially constrained inversions of the AEM data. The resulting models are also compared to drilling information and the resistivity models obtained from inversion of the AMT data. The AEM systems all display different signal and noise levels, and various types of preprocessing. The inversion results are, in general, in good agreement with each other and with the ancillary drilling and AMT information. Some systems however produce inversion outputs with higher accuracy or depth of investigation than others. IP effects, present in portions of the AEM datasets, add another degree of complexity but can also provide an extra layer of information.

WHAT IS ZTEM SEEING OVER THIS TROPICAL PORPHYRY?

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A ZTEM survey over the Cobre Panama mine lease, which highlights most of the known porphyry copper deposits in the cluster, is credited with the discovery of a sixth deposit that will be included in the mine plan. The source of the ZTEM response is within the fresh rock below weathered saprolite and extends to a depth of many hundreds of metres, as does the orebody. The response is at least partly due to the sulphide content of the orebody, both pyrite and chalcopyrite. However, the sulphide percentage of all the deposits is quite low, to a maximum of 3%. A shallow airborne TEM survey also detects a near-surface, fresh rock signature associated with the ZTEM response of each deposit. Thus the TEM response should probably be attributed in part to the associated alteration, mainly sericite, and this will contribute to the intensity of the ZTEM signature as well. Inversion modelling in 2D and 3D indicates the ZTEM is detecting deeper parts of the orebodies, with the correct gross geometries, including the main chalcopyrite mineralisation. These conclusions are supported by analysis of multiple deposits in the cluster.

AIRBORNE GEOPHYSICS OVER THE DOLLY VARDEN VMS AND LOW SULPHIDATION EPITHERMAL SILVER DEPOSITS, NORTHWESTERN BC, CANADA

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Results from helicopter VTEM time-domain electromagnetics that include aeromagnetics and gamma ray spectrometrics and later ZTEM natural field helicopter electromagnetics are compared over the Dolly Varden Mine region that hosts both potential VMS Pb–Zn base metal and low sulphidation epithermal silver mineralisation, beyond the known vein-type Ag deposits and showings.

There are few well-defined discrete targets within the VTEM data set. The magnetic data have defined a network of older fault structures trending NNE, ENE, WNW, and NW. These structures are interpreted to be related to extensional basin formation. Prominent in the radiometrics is a potassium anomaly over the Red Point area, consistent with a quartz-K-feldspar–chlorite–pyrite zone, interpreted as a VMS feeder. ZTEM resistivity and magnetic geophysical anomalies suggest the presence of broad, generally flat lying resistive and magnetic units at depth. At Red Point and along the Tiger-Evindsen Corridor, ZTEM displays moderate to high resistivity and low magnetics, which suggest the presence of strong potassic-silicic alteration, related to low sulphidation epithermal systems.

The airborne geophysical results over the Dolly Varden mine region provide valuable insights on the detectability of similar Ag rich Eskay Creek type HS VMS and Brucejack style LS epithermal deposits. The principal VMS deposits seem immune to clear or discrete identification as EM conductors using VTEM, likely due to their Pb–Zn rich/Cu poor mineralogy; whereas, unlike VTEM, the ZTEM seems to clearly define high resistivity regions surrounding the known deposits that would seem to be consistent with their K-Si-altered low sulphidation epithermal origin.

0830–1010
WEDNESDAY 21 FEBRUARY 2018

8F HARDROCK SEISMIC

POTENTIAL OF FULL WAVEFORM INVERSION OF VERTICAL SEISMIC PROFILE DATA IN HARD ROCK ENVIRONMENT

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Complex structure of the subsurface in hard rock environment often complicates traditional processing and interpretation of seismic datasets based on the analysis of reflected waves. Full-waveform inversion (FWI), in turn, utilises the whole

wavefield, including the transmitted waves and reflections, to build the models of physical properties (such as P wave velocity and density), which is one of its main advantages over traditional methods of seismic imaging. We conduct a feasibility study of 2D full-waveform inversion (FWI) applied to vertical seismic profile (VSP) synthetic data computed in a model that is based on a real hard-rock survey site for the purpose of identification of heterogeneities.

Using this complex model of the subsurface that contains steep interfaces, high seismic wave velocities and densities, we generate a synthetic VSP dataset with a finite-difference code. Multi-offset VSP geometry is considered due to the abundance of transmitted waves. We then apply FWI to this dataset. We use finite-difference modelling for the forward problem in FWI, optimisation is conducted using the limited-memory BFGS method. FWI is applied in a multiscale manner, from 10 Hz to 170 Hz. Inversion results suggest that FWI of VSP data is a suitable tool for building the models of physical properties of the subsurface that are crucial for mineral exploration and mine planning.

THE RISE OF 3D SEISMIC IN HARDROCK MINERAL EXPLORATION

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3D seismic has been a cornerstone of the coal and petroleum industries for decades. And yet, its adoption by the hardrock minerals industry has been much slower. This delay has many causes, with the most obvious being the sheer complexity of acquiring and processing seismic data in a hardrock setting. Fortunately, this topic is the subject of much ongoing research.

A less obvious cause is the limitations of the available software for visualising and interpreting the processed data. Hardrock miners have long enjoyed the flexibility of general mining packages (GMPs) for displaying, analysing, and modelling everything from first-pass geochemical sampling to optimised long-term production scheduling. But these applications are optimised towards massive numbers of drillholes, block (voxel) models, and triangulations, and they perform poorly when asked to display 3D seismic. The result is a massive file, with a long loading time and slow graphics interaction. On the other hand, petroleum software is optimised towards seismic data, but can't handle massive numbers of drillholes.

These limitations can be overcome by incorporating modern gaming graphics technology and efficient file storage platforms within an application, and this presentation concludes by illustrating the results of applied research and development carried out at MICROMINE towards producing a fluid real-time seismic visualisation environment.

FAST-TRACKING GOLD EXPLORATION BELOW 300M – 3D SEISMIC CASE HISTORY FROM DARLOT GOLD MINE

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The Darlot-Centenary gold deposit is one of the larger known mineralised systems in the southern end of the West Australian Yandal Greenstone Belt, with an estimated 3 Moz having been extracted from the Darlot Centenary Mine since 1988. The area is well explored near surface but, given the proven endowment, there is potential for significant additional mineralisation at depth. With current proven reserves dwindling, Gold Fields recognised the need to identify a technology to fast-track target generation in order to more rapidly evaluate the nearby rock volume.

In August 2016 Gold Fields began investigating the potential for 3D reflection seismic to accelerate evaluation of the rock volume accessible via existing workings. In November 2016 a seismic crew was on ground acquiring approximately 150 km^3 of 3D seismic data (25 km^2 surface area × 6 km depth). The survey coverage was designed to image the local steeply dipping geology and structures. Processing of the seismic dataset was completed in Q1 2017 and Gold Fields has completed preliminary interpretation of the 3D cube.

The seismic data has provided a rich 3D picture of the Darlot structural framework to depth, which could not be obtained by any other geophysical method. It has highlighted a number of features with similar characteristics to known mineralisation and has provided a better defined structural framework that has greatly assisted the fundamental geological understanding and further aided ranking of these targets in terms of prospectivity.

DISTRIBUTED ACOUSTIC SENSING FOR MINERAL EXPLORATIOIN: CASE STUDY

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Vertical seismic profiling (VSP) is commonly used in the oil and gas industry for better subsurface imaging and characterisation, as well as for providing depth calibration for surface seismic. The use of VSP in mineral exploration and mine planning is not common at all, mostly due to the small diameter and stability of the boreholes, as well as relatively high cost of such surveys. These issues can be mitigated by using cheap and potentially disposable borehole sensors, such as fibre-optic cables utilised in distributed acoustic sensing (DAS).

The questions we want to answer in this work are how the quality of DAS data compares to other types of borehole measurements, and what are the operational benefits and constraints for the use of this technology in mineral exploration settings. To this end, we have tested performance of DAS measurements in one of the boreholes of The Mineral Systems Drilling Program in South Australia and compared them to hydrophone measurements. The DAS measurements provide data quality that is much better than a hydrophone string, in particular it has consistent amplitudes at different depths, shows less cable and tube waves, and the reflections are much clearer. The acquisition of DAS data is taking a much shorter time than any other borehole measurements

that require multiple pulls of the receivers. The reduction of the acquisition time increases with the depth of the borehole. This case study proves that DAS measurements show big potential for the mineral exploration and exploitation.

0830–1010
WEDNESDAY 21 FEBRUARY 2018

8G GROUNDWATER

IMPACT OF AIRBORNE ELECTROMAGNETIC (AEM) SURVEYS IN GROUNDWATER MANAGEMENT IN THE LOWER PLATTE SOUTH NATURAL RESOURCES DISTRICT, NEBRASKA, USA

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The Lower Platte South Natural Resources District has collected several thousand line kilometers of Airborne Electromagnetic (AEM) data during five surveys beginning in 2007 and continuing through 2016 to develop a hydrogeologic framework for priority groundwater management areas. Frequency domain systems were originally used in 2007 and 2008. A shift to time domain electromagnetics was required to increase the depth of investigation in areas of conductive glacial till beginning in 2013. The AEM surveys were collected as reconnaissance and block flight lines. Careful calibration and diligent inversions were required to maximise resolution of the AEM data. The AEM improved hydrogeologic framework was the basis for changes to the management area boundaries and the type of management controls for many of the areas. The revised Dwight-Valparaiso-Brainard management area has experienced improvements in ground water levels and recent regulation changes have allowed an increase in groundwater pumping in the eastern region. Based on the AEM a new recharge area was identified, and management controls were implemented to reduce non-point source pollution over the recharge area. The AEM derived hydrogeological framework information has been used for the following: to vary management techniques based on degree of aquifer confinement and in-season water declines; to determine the amount of groundwater in storage; to locate potential recharge areas; to guide the installation of monitoring wells; to locate and install surface water gages to understand groundwater-surface water relationships; to locate areas for vadose zone characterisation; and assist local public water suppliers with the management of limited aquifers.

RESOLVING CHANGES TO FRESHWATER LENS SYSTEMS IN A 'SEA OF SALINITY' USING MULTI-DATE AIRBORNE EM

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Saline aquifers in the Murray River or SE Australia are traversed by freshwater rivers, with adjoining riparian and floodplain regions containing freshwater lenses. Bore data and more recent AEM surveys have determined that these lenses are spatially extensive, but have having widely varying geometries. The maintenance of these lense systems is important as they support ecologically significant riparian vegetation communities such as Red Gum and Black Box. A more complete understanding of their hydrogeology is required to ascertain how they develop and degrade. Limited ground investigations including ^{14}C geochemistry have determined that the lens systems contain recent water, indicating that they are dynamic systems with their development defined by the relative rates of recharge from the river and mixing with groundwater. Changes in groundwater gradients and depth, floodplain extent, and topography are believed to control their initial location. The same controls also govern their stability. The potential of airborne EM systems for defining the geometry of these lens systems in 3D is considered along with an assessment of their value for monitoring variations associated with these ecosystems. The advent of 'calibrated' AEM systems and robust inversion tools have given added impetus to their use for monitoring. Spatio-temporal variations are observed in the near surface (top 20 m) from a multi-temporal assessment of Clark's Floodplain, in co-incident airborne EM surveys acquired between 2008 and 2015. Spatial changes in ground conductivity, attributed to changing groundwater quality have been observed. The freshwater lense systems appear to have contracted significantly over the past decade.

STRETCHING AEM NEAR-SURFACE RESOLUTION LIMITS RELATED TO LOW- AND VERY HIGH RESISTIVITY CONTRASTS

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Data from AEM surveys carried out in Norway, to support ground investigations for infrastructure projects, was used in this study. In large infrastructure projects knowledge of sediment thickness is vital, as is information about possible occurrence of highly sensitive clay.

In an area with conductive shales over resistive bedrock, the recently introduced system response method was tested. It's applied in the inversion of SkyTEM data and makes it possible to utilise the very earliest gates. The models showed more pronounced structures in the near-surface, reflecting true structures observed in resistivity borehole measurements. The same outcome was observed when conducting synthetic modelling.

In another setting AEM, measurements were carried out along a planned road project to provide information about the extent of very conductive, possible alum shale. A volume estimate of excavated masses was sought, as alum shale is decomposed to sulfuric acid by weathering. Preliminary AEM models had a tendency to overestimate the thickness of the resistive overburden. Experimenting with the inversion settings resulted in models better fitting other prior information from the area. Limited LM data was available due to a noisy environment. This affected the reliability of the models, illustrated by modelling and resulting real models.

0830–1010
WEDNESDAY 21 FEBRUARY 2018

8H GROUNDWATER

THE 'EXPLORING FOR THE FUTURE' GROUNDWATER PROGRAM: A MULTI-PHYSICS, INTER-DISCIPLINARY SYSTEMS APPROACH FOR DE-RISKING INVESTMENT IN AGRICULTURE IN NORTHERN AUSTRALIA

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The Australian Government has recently provided AU$100.5M to Geoscience Australia over 4 years (2016–2020) to manage the Exploring for the Future (EFTF) program designed to increase investment in minerals, energy and groundwater resources, primarily in Northern Australia. The program includes AU$30.8M for groundwater-specific investigations, recognising that there are major gaps in our knowledge of Northern Australia's groundwater systems and resources. The groundwater component of the EFTF program is focused on addressing these knowledge gaps, with the aim of underpinning future opportunities for irrigated agriculture, mineral and energy development, and community water supply. The groundwater program will include identification and assessment of potential groundwater resources and water banking options in priority regional areas, while also analysing the salinity risk (including seawater intrusion).

To rapidly map, characterise and assess regional groundwater systems and resources in the data-poor 'frontier' areas of Northern Australia, a multi-physics, inter-disciplinary approach has been developed. The program involves the initial use of temporal remote sensing 'data cube' technologies for surface hydrology and landscape mapping, and acquisition of airborne electromagnetic (AEM) and Ground Magnetic Resonance (GMR) datasets. This provides a framework for targeted investigations including passive seismic, microgravity and GPR; borehole geophysics (Induction, gamma and Nuclear Magnetic Resonance (NMR)); drilling and pump testing; hydrochemistry and geochronology (water, landscapes and geology); as well as soils, regolith and basin/bedrock geological, hydrogeological and structural mapping and modelling.

This methodology has enabled rapid identification and assessment of potential groundwater resources, salinity and seawater intrusion hazards, and groundwater dependent ecosystems in several priority regions.

AN INTEGRATED HYDROGEOPHYSICAL APPROACH TO EXPLORING FOR GROUNDWATER RESOURCES IN SOUTHERN NORTHERN TERRITORY

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In Australia's semi-arid and arid interior, groundwater resources provide water supply security for agriculture and community consumptive use and are critical for underpinning economic development. The Southern Stuart Corridor Project in central Australia, is an inter-disciplinary study which aims to better characterise regional groundwater systems and identify the location, quantity and quality of new groundwater resources. The main aims of the project are (1) to de-risk investment in development of a potential agricultural precinct in the Western Davenport Basin, and expansion of horticulture in Ti-Tree Basin, (2) to identify future water supplies for Alice Springs and Tennant Creek, and (3) for regional water supplies for mineral resource development.

The project is funded by Geoscience Australia (GA) as part of the Exploring for the Future (EFTF) Program. The project integrates airborne electromagnetic (AEM), ground geophysics (ground magnetic resonance (GMR) and borehole geophysics (Induction, gamma and nuclear Magnetic Resonance (NMR)) with drilling and pump testing; hydrochemistry and geochronology; and geomorphic, geological, hydrogeological and structural mapping and modelling. Advancements in temporal remote sensing technologies for surface hydrology, vegetation and landscape mapping are also used to facilitate the identification of recharge and discharge zones and groundwater-dependent vegetation.

This paper reports on initial AEM inversion results for the Alice Springs, Ti-Tree Basin, Western Davenport and Tennant Creek areas and the use of a machine learning approach for rapid geological and hydrogeological interpretation of the AEM data. These machine learning approaches have the potential to significantly reduce interpretation time and facilitate the rapid delivery of project results.

USING AEM AND GMR METHODS FOR NON-INVASIVE, RAPID RECONNAISSANCE MAPPING AND CHARACTERISATION OF GROUNDWATER SYSTEMS IN THE KIMBERLEY REGION, NORTHERN AUSTRALIA

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In northern Australia, groundwater investigations in remote areas face challenges including the cost and difficulty in obtaining drilling permit due to lengthy heritage and environmental approvals processes. Non-invasive geophysical techniques, including airborne electromagnetics (AEM), Ground Magnetic Resonance (GMR) and borehole Nuclear Magnetic Resonance

(NMR), are particularly attractive in these circumstances, as key hydrogeological parameters including depth to water table, porosity and transmissivity can be obtained with limited clearance approvals required.

In the Fitzroy Basin of Western Australia, both surface and borehole MR have been applied to groundwater prospectivity assessment of the Cenozoic sediments, and the Palaeozoic and Mesozoic sandstone aquifers. Eight GMR sites were acquired across the basin, which include Mowanjum, Willare – lower Fitzroy, Mount Anderson, and May – Lennard River areas. These sites were selected based on interpretation of the AEM data.

The GMR results with good resolution to 100 m depth were compared against borehole NMR and lithostratigraphic information, and found to be consistent. Both sets of MR data support that the Palaeozoic (Grant Group and Poole Sandstone) are excellent aquifers. At other sites, the lack of water content in some of the water profiles indicates the presence of aquitards such as Blina Shale and Jarlemai Siltstone.

GMR data indicates that the floodplain alluvium of the intermittent Fitzroy River contains little 'mobile', or free-draining, water (~3 vol %) at the end of the dry season. The water table at the site was ~30 m depth, most likely beneath the alluvium in the Mesozoic sedimentary rock.

1040–1220
WEDNESDAY 21 FEBRUARY 2018

9A NEW TECHNOLOGY – SEISMIC

MULTI-COMPONENT SEISMIC: APPLICATIONS AND NEW DEVELOPMENTS

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Multi-component seismic data capture both the vertical and horizontal components of ground motion at the receiver location. The resultant seismic record is a vector entity that enables discrimination between compressional (P) and shear (S) wave arrivals. In practice, conventional P-wave seismic sources are typically used for seismic acquisition. Thus multi-component seismic data refers to the recording of P wave and converted wave (or PS wave) arrivals.

The integrated use of P and PS waves has supported enhanced imaging of the subsurface over the past three decades. This includes 'seeing' through gas-bearing sediments, delineating very shallow reflectors and delivering enhanced near-surface resolution, mapping lithologies and fluids (e.g. sand / shale discrimination, fluid description), and characterising anisotropy (e.g. fracture densities and orientation). When used in a time lapse sense, multi-component seismic data are useful for reservoir monitoring. These applications still remain very relevant to the resource industry today, and a number of more recent examples will be summarised.

However, despite many periods of enthusiasm, use of multi-component seismic data remains challenging. Interestingly, the focus of technical developments today is largely unchanged from the turn of the century. This presentation will provide an overview of current developments. Perhaps most demanding is the requirement to address the very slow propagation of S waves in the near surface. Further, S waves are extremely sensitive to anisotropy and absorption effects. All of these phenomena require careful attention during data processing. What has evolved in more recent times is the ability to work directly with the vector wavefield through full elastic imaging, and joint P / PS seismic inversion combined with more sophisticated P and PS image registration methodologies.

MARINE VIBRATOR CONCEPTS FOR MODERN SEISMIC CHALLENGES

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Aside from fundamental issues of mechanical durability and efficiency, the design of marine vibrators for towed streamer operations are confronted by several very different possible applications: (1) High power alternatives to conventional air gun arrays for flexible and creative acquisition geometries, (2) Low power alternatives to air gun arrays for environmentally sensitive applications, and (3) High power, ultra-low frequency sources specific to Full Waveform Inversion (FWI) optimisation.

One relevant consideration is the volume of water that must be displaced per cycle to achieve a desired Sound Pressure Level (SPL); increasing exponentially as the frequency of interest decreases, and becoming significant at frequencies less than about 5 Hz. This becomes particularly relevant for FWI optimisation as the frequencies of interest are in the range of 1–6 Hz. Another consideration is that ultra-low frequency output theoretically benefits from deeper towing, enhanced by the well-known free-surface ghost effect, but in practice deeper towing is confronted by an air spring effect that increases the force required per cycle to generate a desired SPL, and is due to the surrounding hydrostatic pressure at depth. Other authors have published the design of an extremely large volume vibrator unit that is towed at about 60–120 m as a solution to the air spring effect. However, completely alternative vibrator concepts can be described that either use an array of units with high power drivers or that distribute the water displacement over a large surface area in a creatively efficient manner.

Environmental motivations to develop low power vibrator concepts are driven by regulatory restrictions upon received SPL, Sound Exposure Level (SEL), and cumulative SEL (SEL_{cum}). We describe the design and application of several very different marine vibrator concepts for the three defined applications, and present results from both controlled testing and real data acquisition that illustrate various challenges and their industrial solutions.

FIBRE-OPTIC VSPS: BOREHOLE SEISMIC REVOLUTION IN AUSTRALIA

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The borehole seismic industry is undergoing a quantum leap in the acquisition technology. The standard borehole seismic imaging tools such as accelerometers and geophones are now being replaced by the fibre-optic (FO) acquisition for basic surveys such as zero-offset vertical seismic profiles (ZVSPs) and checkshots. This saves significant time, and associated rig cost, whilst providing sufficient data quality for basic interpretation. Schlumberger's heterodyne distributed vibration sensing (hDVS) technology, deployed within a wireline heptacable, was recently used in Australia to acquire a zero-offset VSP dataset, whilst simultaneously taking downhole core measurements. The hDVS technology is based on the distributed acoustic sensing (DAS). This presentation shows the acquired dataset and the basic processing results. A comparison between the FO and conventional dataset, in the nearby wellbore, as well as surface seismic and synthetics is made showing remarkable similarity between all datasets, validating the FO data.

1040–1220
WEDNESDAY 21 FEBRUARY 2018

9B NEW TECHNOLOGY – CO_2

FEASIBILITY OF SEISMIC MONITORING OF CCS IN PERTH BASIN

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This work studies the seismic response of injection of super-critical CO_2 in Perth Basin, WA, for the purpose of CO_2 sequestration. We aim to propose the most suitable way of monitoring and verification of such storage. To this end, we generated synthetic seismic datasets based on static geological models reflecting various hypothesis about the subsurface properties and fluid flow simulations for different injection scenarios. We investigated in detail two cases:

1. Reference case – the injected CO_2 remains confined in the injection interval, which we aim to characterise quantitatively;
2. Relatively small leakage (~10 kt) into the shaley overburden through a major fault, which we merely aim to detect.

Existing theories of fluid substitution predict small seismic contrasts caused by the injection. Effectively, we cannot rely on the time-lapse changes of the reflection strength, which makes conventional surface-based time-lapse seismic inefficient. However, the fluid flow simulations predict that the buoyancy-driven plumes have significant thickness to allow for the robust detection of the time shifts, which makes seismic pull-down effect more efficient for the time-lapse seismic monitoring of the injection. Furthermore, this feasibility study proves high efficiency of a surface-to-borehole monitoring systems. In particular, results of the full-waveform inversion of the synthetic borehole seismic datasets shows that such a system will allow for the quantitative characterisation of the injected plume.

A DOUBLE DOUBLE-POROSITY MODEL FOR WAVE PROPAGATION IN PATCHY-SATURATED TIGHT SANDSTONE WITH FABRIC HETEROGENEITY

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In natural reservoir rocks, fabric heterogeneity can further induce heterogeneous geometrical distribution of immiscible multi-phase fluid mixture, since fluid migration may be affected by lithological variation (mainly permeability) in geological time scales, causing patchy saturation of fluids. Both structure heterogeneity and patchy-saturation can lead to strong seismic wave dispersion and attenuation. In this work, a double double-porosity model is presented to describe the overlapping effect of the two heterogeneities on wave dispersion and attenuation. The wave propagation equations are derived from the Hamilton's principle, and the numerical results for a tight sandstone are compared with corresponding low-frequency experimental data, which shows good agreements. This new model allows for a comprehensive description of wave propagation process in highly complex reservoirs.

THE INFLUENCE OF REVERSE-REACTIVATED NORMAL FAULTS ON POROSITY AND PERMEABILITY IN SANDSTONES: A CASE STUDY AT CASTLE COVE, OTWAY BASIN

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An understanding of fault zone structure and transmissibility can have significant implications for reservoir appraisal and development within petroleum systems. Previous studies have demonstrated that porosity and permeability is significantly reduced adjacent to fault zones due to pore collapse, grain crushing, and cement precipitation during deformation. We present results from a detailed mineralogical and geomechanical investigation of the Castle Cove Fault within the Otway Basin at Castle Cove, southeast Australia. Castle Cove provides excellent exposures of the Lower Cretaceous Eumeralla Formation, which is a fine-grained volcanogenic sandstone with moderate to highly porosity (up to 27%), but with generally low permeability (mostly <1 mD). The Castle Cove Fault originated as a normal fault during the late Cretaceous and was reverse-reactivated during NW–SE mid-Eocene to Recent compression. Core plugs were sampled at distances between 0.5 to 225 m from the fault and were orientated with respect to the fault plane. We show that closer to the fault (within 75 m), porosity increases by nearly 10% (i.e. from approximately 17% to 24%) and permeability increases by two orders of magnitude (from

0.02 mD to 3.74 mD). Microstructural investigations from thin sections show an increase in microfracture intensities closer to the fault. This study highlights the importance of detailed mineralogical and geomechanical analyses when attempting to understand fault seal generation and reservoir properties in high porosity and low permeability sandstones.

PORTABLE XRD FOR UNCONVENTIONAL AND CONVENTIONAL PETROLEUM EXPLORATION

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Mudlogging traditionally utilised qualitative data, but it recent years has benefited enormously from quantitative mineralogy, in near real time. Conventional petroleum exploration typically utilises a range of quantitative measurements, but quantitative mineralogy onsite is rarely available. Powdered X-ray diffraction (XRD) is a popular method for determining the bulk mineralogy of geological samples. However, due to the capital cost, environmental requirements and significant sample preparation, XRD instruments are rarely deployed to site.

Recent advances in XRD sample holders and X-ray sources have allowed for the development of portable XRD (pXRD) devices where the sample preparation is simpler and does not require regular calibrations by a technical expert. This technology was initially developed by NASA for the Mars Science Laboratory rover Curiosity, to perform mineralogical analysis of the Martian surface.

Due to its portability, minimal sample preparation, fast collection times, and excellent correlation with laboratory-based XRD devices, pXRD has been shown to be of great use to petroleum geologists and engineers by providing rapid, quantitative mineralogical data. For mudlogging quantitative mineralogy is being used to guide directional drilling towards the target formations and to ensure lateral drilling stays within the target formations. Quantitative mineralogy from the target formation and overburden rock also provides important information regarding the engineering properties of these rocks (e.g. fracturability), and can help determine the most appropriate acid for acid-fracturing stimulation. For conventional petroleum exploration quantitative mineralogy onsite, can be used to understand geophysical responses, and as a screening tool for selecting samples for more detailed analysis.

1040–1220
WEDNESDAY 21 FEBRUARY 2018

9C CENTRAL AUSTRALIAN BASINS SYMPOSIUM

REGIONAL MIGRATION AND TRAPPING FRAMEWORKS IN THE FRONTIER CEDUNA SUB-BASIN: NEW INSIGHTS FROM STRATIGRAPHIC FORWARD MODELLING AND 'TRIANGLE JUXTAPOSITION' DIAGRAMS

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In the Ceduna Sub-basin oil-prone source rocks, reservoirs and seals are predicted in Late Cretaceous marine and deltaic sequences. Despite a recent renewal in exploration the sub-basin is underexplored with only one well drilled in the central >10 km thick sequence. Resulting uncertainty regarding lithofacies distribution is high, leading to limited understanding of reservoir and top seal coupling, trends for fluid migration and structural trapping. In the centre of the sub-basin these uncertainties were reduced by using data from a stratigraphic forward model that recreates the development and preservation of stratigraphic successions.

The area of interest covers three distinct structural provinces with basement related faulting and hard-linkage reactivation to the north, listric faulting and soft-linkage reactivation in the centre and listric faulting with upper decollement and local compression to the south.

Pseudo-wells were extracted from the forward model over an area of 9600 km^2 to sample modelled lithofacies, net-to-gross and shale volume distributions and feed 'triangle juxtaposition' diagrams that allow membrane fault seal analysis and oil column height quantification.

This analysis allowed the definition of regional and local net-to-gross distributional trends and the mapping of prospective areas. For both the marine and the deltaic sequences higher prospectivity for reservoirs and structural traps is located toward the north-west of the study area with thicker sandstone packages and reasonable potential of membrane fault seal. A thick Campanian nearshore sandstone units is predicted to act as hydrocarbon migration fairways or potentially form.

COULD THE MESOPROTEROZOIC KYALLA FORMATION EMERGE AS A VIABLE GAS CONDENSATE SOURCE ROCK RESERVOR PLAY IN THE BEETALOO SUB-BASIN?

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The Mesoproterozoic Kyalla Formation (Kyalla) in the Beetaloo Sub-Basin has historically yielded consistent high mud gas shows, and exhibited evidence of oil and gas in cores from exploration wells. Despite positive hydrocarbon indicators, the Kyalla is often overlooked as a potential regional unconventional resource play due to the apparent high clay content (50–70 wt%) thought to affect the potential for effective hydraulic fracture stimulation.

Preliminary petrophysical, core and gas analysis from exploration wells drilled by Origin Energy in 2015–16 revealed positive reservoir quality indicators including high total porosity (8–10% BV), moderate hydrocarbon saturations (40–60% PV), geochemical indicators consistent with an adequate indigenous hydrocarbon source (2–3 wt% TOC, Type I/II Kerogen, VR_{eq} 1.3–1.5) and moderate to high qualitative gas condensate potential as indicated by gas chromatographic analysis on mud gas and drill cuttings headspace gas. Furthermore, geomechanical testing on recovered core indicates properties conducive to hydraulic fracture stimulation.

Fourier transform infrared spectroscopy (FTIR) analysis indicates bulk clay content is primarily comprised of mica species, in particular muscovite. The relative abundance of muscovite over other clay types may play a key role in explaining the observed geomechanical properties of the Kyalla despite its overall high bulk clay content.

If the Kyalla is technically viable, it will add an alternative or additional play in a basin that has the potential to be key to long term supply stability to domestic and export gas markets.

ISOTOPE CONSTRAINTS ON INTRA-BASIN CORRELATION AND DEPOSITIONAL SETTINGS OF THE MID-PROTEROZOIC CARBONATES AND ORGANIC-RICH SHALES IN THE GREATER MCARTHUR BASIN, NORTHERN TERRITORY, AUSTRALIA

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The greater McArthur Basin in northern Australia forms the world's oldest potential unconventional gas play. It comprises Paleo- to Mid-Proterozoic sedimentary successions of the McArthur and Birrindudu Basins, which are likely linked in the subsurface. The Mid-Proterozoic sedimentary record in these basins is dominated by carbonate rocks (i.e. dolostones) deposited in various shallow marine to more restricted lagoonal and sabkha/playa evaporitic environments, while the associated organic-rich shales (i.e. the Barney Creek and Fraynes Formations) likely formed in relatively deeper and/or redox stratified depositional settings.

Here we use a multi-proxy approach based on the isotope tracers of strontium ($^{87}Sr/^{86}Sr$), carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) to further constrain the plausible paleo-depositional environments, and to test the applicability of these proxies for intra-basin correlations in the greater McArthur Basin. Specifically, we will present the first continuous high-resolution Sr, C and O isotope records acquired from two drill cores, Lv09001 and Manbulloo-S1, intersecting the above Mid-Proterozoic (~1640 ± 5 Ma) organic-rich sedimentary sequences in the McArthur and Birrindudu Basins, respectively.

Importantly, our preliminary data from a drill core Lv09001 in the central McArthur Basin, which comprises dolomites and organic-rich shales (Barney Creek Fm.), show systematic variations in carbonate-based $^{87}Sr/^{86}Sr$ and $\delta^{13}C$ proxy records that are tightly coupled to changes in a local depositional environment, the latter interpreted as oscillations between relatively open-marine (oxic?) to more restricted (anoxic) conditions. We will further test whether the above isotope changes recorded in Lv09001 can be traced across the greater McArthur Basin, by comparing these data with presumably coeval sedimentary sequence from Manbulloo-S1 core (i.e. Lymbunia Group, with organic-rich Fraynes Fm., dated at ~1640 Ma), sampled in the adjacent Birrindudu Basin. Conclusions will be made regarding the purported connectivity of the McArthur and Birrindudu Basins, and the suitability of our multi-proxy isotope approach for the intra-basin correlations.

RANKING DHI ATTRIBUTES FOR EFFECTIVE PROSPECT RISK ASSESSMENT APPLIED TO THE OTWAY BASIN, AUSTRALIA

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The first evidence of seismic brightening linked with gas charged reservoirs was revealed in the early 1970s in the Gulf of Mexico. Since that time the terms bright-spots, flat-spots, AVO anomalies or gas anomalies have been used interchangeably (and often loosely) to imply positive evidence exists for gas charge of a prospect.

A seismic Direct Hydrocarbon Indicator (DHI) is an anomalous seismic attribute or pattern that could likely be explained by the presence of oil or gas in a reservoir. Conformance with depth structure is the primary attribute for ranking the quality of a DHI anomaly. It is very difficult to generate this conformance with depth structure in the absence of hydrocarbons. AVO anomalies and bright spots conversely may be generated by numerous lithological or seismic processing related phenomena.

By assessing the key criteria that determine the quality of a DHI anomaly associated with proven gas accumulations, it is possible to build a catalogue of DHI anomalies calibrated to known gas accumulations. Application of the DHI quality factor to modify the initial chance of geological success (Pg) is crucial to objectively grading drilling opportunities.

Two key questions arise:
(1) If DHI anomalies are so 'easy and powerful', why have there been so many DHI supported dry holes drilled around the world?
(2) If strong DHI anomalies are highly correlated with gas discoveries, how often is the lack of a robust DHI anomaly used to downgrade a prospect?

We use historical data from the Otway Basin to offer some answers

1040–1220
WEDNESDAY 21 FEBRUARY 2018

9D EXPLORATION STRATEGY

BUDGET ALLOCATION AND THE STOPPING PROBLEM IN MINERAL EXPLORATION

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Most greenfields mineral exploration projects involve a process of testing targets that have been selected on the basis of geoscientific data. Although this data can be used to rank targets questions still arise as to how many targets should be tested before the area is dropped. This paper addresses this question with a probabilistic model of the exploration process and illustrates the method with a geophysical example.

It is shown that an exploration project should terminate when the Return on Investment (ROI) obtained by testing another target falls below that of other opportunities. In general the ROI for each target is different and is a function of the Likelihood Ratio $L = P_d/P_{fp}$. Where P_d is the probability that a mineral occurrence with the target's geoscientific parameters will be detected *and* P_{fp} is the probability that the same parameters will cause a false positive. In addition to these variables the model assumes fixed probabilities of finding a mineral occurrence without data and of a mineral occurrence being economic. Normal valuation and cost estimates complete the fixed parameters.

Clearly, the way L is constructed is critical to the whole process and, depending on the exploration strategy, might be very subjective. However, when simpler rules of the type often applied to geochemical or geophysical anomalies are used, it is possible to develop algorithmic approaches to define L. An example using geophysical data for kimberlite exploration will be discussed.

HOW A SYSTEMS THINKING APPROACH TO MINERALISING GEOSYSTEMS IS OPENING NEW SEARCH SPACES FOR ORE DISCOVERY

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Systems thinking is used to study interactions. It is different from simple event orientated thinking that implies chains of cause and effect along a time line. In systems, the systemic behaviour emerges from its structure, the flows and feedback loops, rather than any individual element. Mineralising geosystems and ore systems are often complex and self-organising. As mineral explorers it is unlikely that we will be able to truly understand complex mineralising geosystems if we do not understand the systems theory. Mineralising geosystems operate at different scales at different times and sometimes at several scales at the same time. By using systems theory tools we can beginning to close the gap in predictive targeting effectiveness between the regional and camp scale to unlock new search spaces. Feedback loops leave evidence in the geological record that can be measured and mapped.

A mineralising geosystems map for tin deposits, shown at Target 2017, has been extended and analysed using Stella and yEd software. Tin was chosen as an example of a well-studied simple magmatic mineral system. The mineralising geosystem map has already challenged several paradigms that also apply to other mineralising geosystems.

Most giant mineral systems are formed within a few kilometres of the Earth's surface. To ignore the role and overlap of the hydrosphere, biosphere and atmosphere systems in the upper crust is to miss important feedback loops.

1040–1220
WEDNESDAY 21 FEBRUARY 2018

9E GEOPHYSICAL CASE HISTORY

IMAGING HIGH QUALITY CONDUCTORS AT GOLDEN GROVE

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The success of the DHEM method in detecting the Gossan Valley mineralisation, south of Gossan Hill mine, in 2008/2009 led to the systematic application of the DHEM method across the Golden Grove lease from 2011 to 2014. The method proved successful in identifying several new zones, including the Grassi resource. During these surveys it was noted that the EM method failed to elicit either in-hole or off-hole responses in a number of holes with economic intersections of lead, zinc and precious metal ore. It became clear that not all economic ore zones contained sufficient conductive sulphide to ensure detection using DHEM. This triggered an assessment of available methods to determine if other down-hole technologies could be used to complement the DHEM method.

A program of core petrophysic measurements and petro-physical borehole logging led to the realisation that because the host rocks were very resistive there existed a sufficient contrast for high frequency EM imaging to be viable. This led to a trial of the Radio Imaging Method at the Xantho resource of the Gossan Hill Mine in December 2016. The results of the trial suggested direct detection of the massive sphalerite ore is possible. Further work is being undertaken to better understand the optimum survey methodology in the Golden Grove Mine environment with a view to providing specific recommendations that if approved will see the use of the method expanded on the mine leases, both at Gossan Hill and Scuddles mines, as well as on the surrounding mine leases.

WOODLAWN REVITALISED BY DHEM

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This paper presents the critical and thought-provoking role DHEM has played in revitalising the Woodlawn mine since

2012. Woodlawn, a well-known volcanic-hosted massive sulphide deposit in New South Wales, had been dormant since mine closure in 1998. Attempts to reopen were stymied. DHEM surveys had been little used due to a general view that the mineralisation was poorly suited to EM. Despite this preconception, a deep exploration hole was approved for DHEM and importantly, the entire length of hole would be surveyed 'just in case'. The result was a large offhole conductor recorded in the upper portion of the survey, in an area considered very well tested by previous drilling. The resultant high grade discovery of the ~1 Mt 'Kate Lens', as well as several subsequent discoveries, many using DHEM, means that Woodlawn is now on track to reopen in the near future. This case study illustrates the importance of the 'never assume' approach to exploration, as well as the value that DHEM can add to exploration projects.

MINERAL EXPLORATION IN THE MOUNT LYELL REGION OF TASMANIA WITH THE HELITEM$_{35C}$® SYSTEM

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The Mount Lyell region contains more than 20 significant mineral deposits with 150 MT @ 1.23% Cu 5 g/t Ag and 0.35 g/t Au having been extracted. Many of the ore bodies occur along or near the Great Lyell fault, which is west-dipping and shows a complex history of movement. Significant reverse movement has occurred on the fault juxtaposing older volcanics against younger sediments to the east. Copper deposits are mainly disseminated pyrite-chalcopyrite and occur as sub-vertical pipes. Although historic ground EM surveys conducted in the 80s were not successful more recent CSAMT surveys did indicate that some of the known orebodies do exhibit a good conductivity contrast to the generally restive host. Transient EM DHEM utilising a large transmitting loop at surface did lead to the discovery of a new deposit.

Here we provide a case study of recent exploration work in the Mount Lyell region. We describe the geologic history around Mount Lyell and exploration activities. Recently an airborne electromagnetic survey was performed, using CGG's Helitem$_{35C}$ system with the MultiPulse waveform (both halfsine and square wave pulses are generated in a single waveform). We describe the Helitem$_{35C}$ results, along with 2D/3D inversion modelling, and how they fit with the known geology. A number of undeveloped mines were detected by the system and the data will be used to target possible extensions of the known ore bodies.

COMBINED GRAVITY AND MAGNETIC STUDIES OF SATELLITE BODIES ASSOCIATED WITH THE GIANT COOMPANA REVERSE MAGNETIC ANOMALY IN SOUTH AUSTRALIA

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The Geological Survey of South Australia has recently acquired ground gravity data to accompany the airborne magnetic survey over the Coompana Area of southwestern South Australia. The new gravity data reveals that the several negative magnetic anomalies, which accompany the giant (60 km diameter, 2000 nT range) main Coompana negative magnetic anomaly have corresponding well-defined positive gravity anomalies. All but one of these satellite magnetic anomalies can be matched with models of simple geometry and homogeneous remanent magnetisation. Similarly, all of the corresponding gravity anomalies can be matched with simple geometry, homogeneous density contrast models. However, only one of the density and magnetisation model pairs is self-consistent, revealing that these bodies do not have an internally consistent magnetisation to density relationship, and that at least one (probably both) of the property distributions are variable through the bodies. We present modelling of three of these bodies with magnetic and gravity ranges respectively of 800 nT and 15 μm/s^2, 5000 nT and 90 μm/s^2, and 3000 nT and 100 μm/s^2. A drilling program is underway, which should reveal the geological nature of the bodies, and also allow us to make direct density and magnetisation measurements. With these constraints available, we expect to construct models which more reliably reconcile the gravity and magnetic data. However, with no more than one hole into each body, and with those holes unlikely to reach the base of the bodies, there is still considerable interpretive challenge in this task.

1040–1220
WEDNESDAY 21 FEBRUARY 2018

9F PETROPHYSICS

THE USE OF PETROPHYSICAL DATA IN MINERAL EXPLORATION: A PERSPECTIVE

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Recognising targets for testing and accurately mapping the geology are equally dependent on petrophysics, which constitutes a link between the geologist's largely mineralogical 'view' of the Earth and the geophysicist's physics-based 'view'. Despite their critical importance, petrophysical datasets tend to be small, are often collected in an ad-hoc fashion and are often not analysed in detail.

Semi-automated scanners are available which can rapidly make simultaneous, multiple, geochemical, mineralogical and physical property measurements. This allows larger volumes of petrophysical property data to be collected, and in a better geological context, than has been possible in the past. This is important because many rock physical properties are extremely heterogeneous and a large number of data is required. Accurate interpretation of the data requires analysis of the data as populations and in the context of all of lithology, alteration, stratigraphy and spatial location.

I will describe new ideas on the classification of petrophysical properties and their analysis and also suggest ways to better present these data in a geological context. A key message is that the current, largely lithology-based, approach is not optimal. In most cases it is essential to also consider alteration and porosity.

The proposed approach will be illustrated using case studies involving (1) altered ultramafic rocks from Archaean greenstone terrains, (2) dolomitised carbonate successions hosting base-metal mineralisation, (3) carbonatites associated with REE mineralisation and (4) mapping geology in the Broken Hill region.

PRACTICAL CONSIDERATIONS AND GOOD PROTOCOL FOR THE INTERPRETATION OF ULTRAMAFIC AND MAFIC ROCK PHYSICAL PROPERTY DATA

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An increase in the availability of inexpensive and easy-to-use geophysical tools has led to the interest in collection of larger rock physical property databases. More notably, magnetic susceptibility and density measurements are routinely made on drill-core specimens. These data are often interpreted at face value, with little consideration given to the selection of representative samples, sample preparation, or even the practical limitations of measuring tool. Consequently, uncertainty is unnecessarily inflated, and a diminished benefit perceived.

Bivariate-Henkel plots of multi-petrophysical data are useful in identifying key lithotypes and subpopulations that may be attributed due to alteration or mineralisation. These plots can form a basis from which to rank the applicability of geophysical methods, and may provide a means from which to select a third geophysical method that provides an optimal solution to constrain geology in a physical property driven model. P-wave velocity, magnetic susceptibility and density data are considered most common, and are discussed in detail. The use of p-wave velocity and density data are of great importance particularly when determining the acoustic impedance of rocks and the suitability of seismic programs.

Although less common, it is recommended that bivariate plots be used to compare petrophysical data derived from a variety of tools or measurement processes. Here, the validity of historical data may be better evaluated, e.g. the effect of volumetric problems, which is inherent of dry-bulk density, is discussed; as is the appropriateness of commonly employed electromagnetic-based magnetic susceptibility meters compared with Qmeter derived data using same samples.

PETROPHYSICS AND EXPLORATION TARGETING: THE VALUE PROPOSITION

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There is still much that needs to be understood about the physical properties of rocks in mineralised geological environments. This knowledge gap becomes more important as the transition to deeper exploration targets under cover occurs, with an associated greater reliance on geophysical exploration methods. The major challenge associated with understanding petrophysical data is not making the measurement, but rather understanding the results. The interpretation of the data is a cross disciplinary problem. Fundamentally it is necessary to understand the rock mineralogy and geochemistry to put the petrophysics in context with the geophysical results. Several case studies are presented where the petrophysics have determined not only which geophysical techniques to apply but whether a geophysical target has indeed been tested. For example, the sedimentary textures associated with sediment hosted copper mineralisation can compromise the inductive conductivity and resistivity response (anisotropy). Chargeability highs associated with porphyry copper mineralisation is indicative of disseminated pyrite in the propylitic and pyrite ± chalcopyrite ± bornite in the potassic alteration zones and higher chargeability does not necessarily mean more copper. Drill testing EM plate approximations for nickel sulphide and volcanogenic massive suphide (VHMS) ore deposits can benefit from inductive conductivity measurements on core as it can determine whether an EM conductor has been intersected. In most porphyry systems magnetite is coarse-grained, therefore a world class porphyry deposit should not have dominant remanent effects and the only likely source of remanence features in younger terrains are oxidised mafic intrusions and skarns.

DEFINING PETROPHYSICAL PROPERTIES OF ULTRAMAFIC AND MAFIC ROCKS IN TERMS OF ALTERATION

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It has become common practice to categorise rock physical property data solely by lithotype. This has led to the development of wide distributions in range within global petrophysical databases, as well as localised studies. Consequently, an uncertain relationship between reliable rock physical properties and geology is ever present. Characterising rock physical property data by alteration may mitigate this uncertainty. The use of mineralogical scanners, e.g. hyperspectral, and portable whole-rock geochemical analysers, e.g. pXRF, are able to put the petrophysical data in a correct mineralogical context while reducing the subjectivity of the interpretation of type and variable degree of alteration, which are often made by an individual geologist.

The effects of talc-carbonate alteration and serpentinsation on physical properties of ultramafic rocks are regularly presented but often within incomplete datasets, and as such, are poorly understood. The development of an integrated and more robust database is important. Consequently, two Western Australian greenstone terranes have been studied. Data from over 1000 samples taken from the Plutonic-Marymia Greenstone Belt and Eastern Gold Fields region are presented. New p-wave velocity, magnetic susceptibility, density, natural remanent magnetisation, hyperspectral and whole rock geochemical data are examined. An integrated approach of placing empirical petrophysical data within a rigorous mineralogical and petrological framework is undertaken. Consequently, this study is able to advance petrophysics beyond its current dominantly-data-acquisition phase towards a process-based predictive capability, serving to better understand alteration while providing a new mechanism from which to potentially vector toward mineralisation.

1040–1220
WEDNESDAY 21 FEBRUARY 2018

9G GROUNDWATER

THE USE OF AIRBORNE EM TO INVESTIGATE A COASTAL CARBONATE AQUIFER, SEAWATER INTRUSIONS AND SUSTAINABLE BOREFIELD YIELD AT EXMOUTH, WESTERN AUSTRALIA

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Exmouth is a regional center located 1260 km north of Perth, Western Australia, that relies entirely on groundwater for its water supply. Its borefield extracts groundwater from an unconfined carbonate limestone aquifer within the Cape Range Group. Groundwater flows easterly from Cape Range to Exmouth Gulf where it discharges above a saline wedge at the base of the aquifer. The current borefield extraction has insufficient capacity to meet increased water demand due to population growth and the influx of tourists in holiday periods.

In 2016–2017, the Water Corporation decided to investigate optimising borefield performance through improved production from existing infrastructure. An Airborne Electromagnetic (AEM) survey, desktop review, 3D modelling, and pumping tests, helped define the extent/geometry of the saltwater interface and karstic features within the aquifer.

The AEM survey effectively mapped saline water. It identified existing bores in areas with lower salinity and away from the saline wedge. Twenty-four hour pumping tests of these bores was undertaken at rates much higher than their current extraction rate. The survey also identified existing bores in areas of higher conductivity where increased extraction is not recommended.

The AEM survey and new hydrogeological modeling have established a clear relationship between the extent of the saltwater interface, and the location of karstic features. Importantly, bores have been identified which could accommodate additional sustainable extraction. Other bores have been identified where extraction rates should not be increased, or should be reduced.

DEVELOPING WATER SUPPLIES FROM SAPROLITE REGOLITH

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Extensive areas of saprolite regolith are present on plateau land development over cratonic regions of the earth. These saprolite zones often contain significant water saturated sections and represent large storages of groundwater.

Groundwater storages in saprolite, although widely used for village and small rural supplies, particularly in subtropical regions where groundwater is at a shallow depth and of low salinity, are rarely developed as major water sources.

The principal reason for lack of usage of saprolite regolith results from inherent low to very low hydraulic conductive properties.

Much knowledge of saprolite hydrogeology has been gained through development of open pit mines in these rocks. Long term observations show that a considerable portion of dewatering results from drainage from saprolite rather than from the limited storage of fracture zones containing dewatering bores mostly sited in underlying crystalline rock.

This paper describes examples taken from widely separate climate regions of the earth where saprolite has been dewatered through use of underdrainage from linear structures in the bedrock. Underdrainage makes use of both inherent palimset structures in saprolite as well as the ‘delayed yield’ factor familiar in development of phreatic aquifers. This underdrainage has resulted in large sustained groundwater yield from the region.

Knowledge gained from open pit mine dewatering has provided sound examples on water storage and potential extractable storage values from saprolite. This knowledge has proven valuable when applied to planning water supplies from underdeveloped saprolite regions particularly those is arid plateau lands that lack alternative water sources.

FOCUSED ATTRIBUTES DERIVED FROM AEM SURVEYS USING THE CONTINUOUS WAVELET TRANSFORM

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Interpretation of a hydrogeophysical survey is a complex and comprehensive process. In addition to an areal coverage with AEM data, most often an interpretation involves additional data that are time consuming to collect and complicated to integrate into an overall model, e.g. borehole logs, borehole core samples, water chemistry, surface vegetation, satellite imagery plus the generally accepted geological background knowledge. Compared with the complexities of the interpretation process, the acquisition, QC and inversion of AEM survey data are a more straightforward affair and considerably less time consuming.

Interpretation basically has to do with identifying categories and finding boundaries between them so that depths, thicknesses, lithologies and a whole range of other model attributes can be estimated, qualitatively and quantitatively. To supplement the traditional product delivered by the inverter to the interpreter: inversion models displaying the distribution of subsurface electrical conductivity, I present two methods based on the Continuous Wavelet Transform that can deliver more focused attributes to assist the interpreter. In the first method, layer boundaries in the smooth multi-layer models that are most often used in the inversion of large data sets are found. In the second method, the spatial distribution of the natural categories of the model parameter is found. Both methods are based on the inversion models and, evidently, they are useful to the extent that the variations in conductivity reflect geological/hydrogeological boundaries and categories – which is for the interpreter to decide.

STRUCTURAL ANALYSES AIDING IDENTIFICATION OF WATER CONDUCTIVE FRACTURE ZONES IN CRYSTALLINE ROCK

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Development of hydraulic conductive zones in crystalline rock can result from a wide range of geological conditions that include primary structures, post crystalline tectonics, fluid solution and movement within a developing and eroding regolith.

Crystalline rock areas mostly have low water resource potential due to inherent extremely low storage and water conductive properties. Therefore, fracture zones of high hydraulic conductivity have an important role in developing groundwater resources in these areas.

Mechanisms for development of open tension or pull-apart fractures in brittle rocks are similar to those involving development of mineralised veins. The same structural analytical techniques can be applied.

Crystalline rock fracture zones can be amenable to rapid recharge through rainfall runoff. They are also significant in that they provide a mechanism for underdrainage through 'delayed yield' of surrounding or enclosing low conductive rocks such as saprock/saprolite, pelite and phyllite.

In addition to brittle rocks, open tension fracture zones of enhanced hydraulic conductivity may also occur in more fissile pelitic rocks such as slate and phyllite. These zones are often associated with crestal zones of folds and along saddles in cross-folds and in strike deviations produced by conjugate shears.

The development of conjugate joint sets in a region also provides a significant basis for this type of fracture analyses.

This presentation provides examples of water supplies developed from crystalline rock structures in a range of geological and earth environments.

1040–1220
WEDNESDAY 21 FEBRUARY 2018

9H GROUNDWATER

COMPARATIVE EVALUATION OF 1D, 2.5D AND 3D INVERSIONS FOR RESOLVING TECTONIC ELEMENTS IN FLOODPLAINS AND NEAR-SURFACE INVERTED SEDIMENTARY BASINS

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This study reports the results of a comparative evaluation of 1D, 2.5D and 3D AEM inversions for resolving hydrostratigraphy and structural elements in two contrasting settings: unconsolidated Quaternary floodplain sediments affected by Neogene deformation; and a tectonically inverted Palaeozoic sedimentary basin.

Previous studies have demonstrated the importance of airborne electromagnetic (AEM) data optimisation to ensure that key elements of the hydrogeological system, including geological faults, are appropriately represented in inversion models. In the inverted sedimentary basin study, 1D inversions of AEM data indicated greater structural complexity than previously known. Initially, a suite of equivalent 1D inversion models produced very similar inversion model results. However, 2.5D inversions produced a disparity in solutions in key locations. To resolve these differences, 3D AEM inversion methods have been trialled. In the second study (floodplain setting), 3D inversions have helped resolve the geometry of hydrostratigraphic units and tectonic elements (folds and faults). In both study areas, independent validation of inversion results has involved an inter-disciplinary approach incorporating a range of borehole and ground geophysics techniques (e.g. passive seismic and Ground Magnetic Resonance (GMR)), tectonic mapping and analysis, hydrochemistry and drilling.

In summary, comparative evaluation of 1D, 2.5D, and 3D AEM inversions in two contrasting settings demonstrates the importance of optimising inversion procedures, taking into consideration all available geological, hydrogeological and tectonic data. The benefits of using 2.5D and/or 3D inversion procedures are particularly evident in areas of structural complexity. Confidence in 3D inversions is maximised when all elements of the system response are modelled appropriately.

RAPID ASSESSMENT OF GROUNDWATER SALINITY AND SEAWATER INTRUSION HAZARD IN THE KEEP RIVER FLOODPLAIN, NORTHERN TERRITORY, AUSTRALIA

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The Australian Government's White Paper on Developing Northern Australia recognised that expanding the size of the Ord irrigation area in the Kimberley Region, northwest Australia offers the potential to significantly enhance both the profitability and economic resilience of the region. This paper reports on the preliminary results of hydrogeological investigations in the Ord Stage 3 development area, a 14 500 ha area of black soil plains in the Keep River floodplain, Northern Territory.

Previous investigations in the Keep River floodplain identified potential for groundwater salinity, soil salinity and seawater intrusion (SWI) hazards. These earlier studies recognised that more comprehensive investigations were required to fully assess the risks of large-scale development of irrigated agriculture on groundwater quality and quantity. The Keep River Salinity Mapping Project has been established to provide baseline data on the groundwater system in the Keep River floodplain including aquifer and aquitard distribution and properties, and potential salinity hazards. Specifically, the main aims of the project are to: (1) map the 3D architecture and hydraulic properties of the soil, sub-soils and underlying paleovalley system; (2) map the SWI interface and variations in groundwater salinity; (3) identify potential surface water inundation risks; (4) identify groundwater-dependent ecosystems; and (5) carry out a hydrogeological assessment. Investigations include a program of airborne electromagnetics (AEM), ground geophysics (ground magnetic resonance (GMR), passive seismic and microgravity), drilling and borehole geophysics, hydrogeological and hydrochemical investigations, and regional soils, geological and morphotectonic mapping. Products generated in this project will be used to parameterise a numerical groundwater model.

VTEM ET: AN IMPROVED HELICOPTER TIME-DOMAIN EM SYSTEM FOR NEAR SURFACE APPLICATIONS

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Sampling the earliest possible transient EM decay in time-domain airborne electromagnetic data (TDEM) is critical for shallow near surface applications. In an effort to further improve near-surface resolution, starting in late 2015 and into 2016, Geotech Ltd developed its new VTEM ET system that uses a re-designed broadband receiver sensor, a re-configured transmitter system, and a new digital acquisition system to achieve precise, distortion free measurements of the time-domain EM decay as early as 0.005 ms after the transmitter turn-off. The new receiver features a much larger frequency bandwidth for lower distortion measurements. The new transmitter delivers a sufficiently high dipole moment, a long pulse-width and faster turn-off time than previous systems, but similarly using a single transmitter pulse. The new digital acquisition system operates at a much higher sampling rate, with significantly more decay channels, particularly in early times, and with low noise levels. The result is a new category of VTEM system that is specifically is designed for precise near-surface applications, such as groundwater and environmental problems, as well as in mineral exploration for lode gold and alluvial deposits, along with sufficient depth of investigation.

We present forward modeling and field survey test results comparing the VTEM ET system with our standard VTEM Plus system with full-waveform processing over a groundwater project with ground geophysical and borehole controls in the upper 30–50 m.

1345–1500
WEDNESDAY 21 FEBRUARY 2018

10A NEW TECHNOLOGY – SEISMIC

LEAST SQUARE Q-KIRCHHOFF MIGRATION: IMPLEMENTATION AND APPLICATION

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Absorption effects caused by the anelastic nature of the earth leads to the attenuation of amplitude and distortion of phase of seismic waves. Conventional acoustic migration, formulated as the adjoint operator of forward modelling (Claerbout, 1992), cannot account for this effect due to the non-unitarity of the modelling operator in highly attenuative geologic environments. This may produce images with poor illumination, reduced resolution, and wrong placement of reflectors. The so-called quality factor 'Q' accounting for this absorption effect has to be included for correct imaging. The two main challenges in Q compensation are the ill-posed nature of the problem and the complex absorption patterns along ray paths in real geological structures. Conventional 1D inverse Q-filtering fails to address these two challenges and are only applicable under limited circumstances. Xie et al. (2009) proposed Q pre-stack depth migration (QPSDM) which compensates for absorption during migration by fully honouring ray paths, however, the ill-posed nature is still not well-addressed in the approach. This may result in over-boosted noise and migration artefacts masking high dipping structures including faults. Moreover, the anti-alias implementation in Kirchhoff migration further reduces the compensation of high dipping structures. To tackle the instability caused by the ill-posed nature of the problem as well as maintain the correct compensation for high dipping structures, we propose least squares Q-Kirchhoff migration (LSQPSDM) in which absorption is incorporated into the Kirchhoff modelling operator and Q compensation is achieved naturally via inversion with proper sparse constraints. The regularisation consisting of prediction filters from reference substacks and sparse constraint in image domain is built into our inversion process to reduce migration artefacts and improve both common image gathers and

the stack image. With better illumination and Q compensation, fault imaging is naturally enhanced through the proposed least squares Q-Kirchhoff migration. In contrast to standard least squares Kirchhoff migration, in our approach the inversion is approximated by inverse Hessian filtering (Wang et al., 2016; Khalil et al., 2016) to give a cost-effective solution. The proposed LSQPSDM approach has been applied to synthetic data for validation and a field dataset from NWS Australia. Better fault imaging and SNR are obtained compared to conventional Q migration.

MODELLING COMPLEX NEAR-SURFACE FEATURES TO IMPROVE SHALLOW SEISMIC EXPLORATION

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Land seismic exploration is often limited/impacted by complex structures in the near surface. These can include large variations in velocities caused by weathering (low velocity) or basalts (potentially high velocity).

Timing changes due to near-surface velocity variations are often accommodated by applying statics corrections during seismic processing. Shallow coal exploration requires high-resolution data to image structures and faulting. A good understanding of these is required for both safety and economic reasons. However, in some cases small errors in statics correction may have a significant impact on the viability of the use of seismic data in these complex environments.

Often near-surface structures also show non-planar characteristics which may attenuate or further complicated the seismic response.

In this paper we use finite-difference visco-elastic modelling to investigate the impact that a number of common near-surface structures have on seismic data. This modelling has been used to determine the optimal acquisition and processing parameters required for a seismic program in order to achieve desired results.

1345–1500
WEDNESDAY 21 FEBRUARY 2018

10B NEW TECHNOLOGY – CO_2

CA-IDTIMS AND BIOSTRATIGRAPHY: THEIR IMPACT ON EXPLORATION

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Uranium-Lead zircon dating using Chemical Abrasion-Isotope Dilution Thermal Ionisation Mass Spectrometry (CA-IDTIMS) has largely overcome the problem of radiogenic lead loss, which gave ages significantly younger than that of crystallisation. Previous techniques gave 95% confidence intervals of 1% or worse, whereas CA-IDTIMS can deliver 95% confidence intervals of 0.1% or better. This has major implications for the correlation of strata.

Previous techniques allowed the dating of formations, subgroups or groups, but we can now date individual beds in a succession and provide a much better understanding of the timing of volcanic events and sedimentation rates. However, perhaps the most important facet of this new technique is the ability to date biostratigraphic zones. Previously, zones were calibrated against the numerical timescale often by a three-stage correlation. For instance, in the Permian, eastern Australian palynological zones were correlated with Western Australian palynological zones, on the assumption that they were coeval. Then limited Western Australian conodont or ammonoid occurrences were used to correlate to northern hemisphere zonal schemes, which form the basis for the international Geological Time Scale. Each of these steps added a degree of uncertainty that is rarely, if ever, quantifiable. The result is essentially presented as the best available estimate.

Where ash beds are common, the new technique allows robust calibration of biostratigraphic schemes directly to the numerical timescale. These new calibrations are often considerably different from those preceding them, and have a significant effect on age-depth plots, and thus burial history models, used in the petroleum industry.

ANALYSIS OF TIME-LAPSE SEISMIC AND PRODUCTION DATA FOR SYSTEMATIC RESERVOIR MODEL CLASSIFICATION AND ASSESSMENT

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The heterogeneous distribution of reservoir properties is one of the most important uncertainties in static and dynamic reservoir modelling. Petrophysical properties are usually interpolated within reservoir models from sparse well-log data, which can lead to highly uncertain estimates at inter-well locations that directly affect the reliability of fluid-flow model predictions of reservoir behavior. To address this issue, we build an ensemble of equiprobable models that combine different geostatistical realisations of reservoir properties to span the range of potential outcomes. While this process captures the impact of reservoir property distributions on the model response, a major challenge is classifying the subset of models in the ensemble best representing reservoir fluid-flow behavior. Thus, we introduce a methodology combining 4D seismic amplitude attributes and reservoir production data to classify fluid-flow models. This classification is based on applying thresholds for independent seismic and production objective functions. We test our methodology on the benchmark case UNISIM-I developed from observations from the Namorado Field, Campos Basin, Brazil. By comparing injection and production rates in relation to 4D seismic amplitude trends, we identify nine models out of an ensemble of 100 that judged optimal via the required seismic and production objective function thresholds and obtain an improved

quantitative evaluation of the impact of reservoir production on the 4D seismic signal. Ultimately, combining seismic and production data offers interpretation scenarios that automatically identify realistic fluid-flow models that can assist the update of permeability and porosity distributions within the reservoir.

INTEGRATING GEOPHYSICAL MONITORING DATA INTO MULTIPHASE FLUID FLOW RESERVOIR SIMULATION

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Simulation of multiphase flow systems are of critical importance in managing hydrological systems. Flow simulations are affected by a number of factors including structure and flow properties including porosity and permeability as well as the anisotropy and heterogeneity of these properties. In many cases traditional hydrological and reservoir data are highly affected by these parameters, but are not directly sensitive to them. As such modellers often adjust these parameters in an *ad hoc* manner until solutions numerically converge. Simulation models are generally based on structural data from reflection seismics whose physical flow properties are then populated using geostatistical extrapolation techniques utilising a sparse number of borehole logs and core analysis. In multiphase systems, including enhanced oil recovery and carbon capture and sequestration, uncertainties regarding phase-dependent physical properties confounds this challenge further. Geophysical methods provide a means by which to gain an improved understanding of phase distributions in the subsurface. In this paper we will look at applications from active carbon capture and sequestration and enhanced oil recovery applications, as well as synthetic examples. Geophysical data including electromagnetic and gravity are inverted using structural constraints from the reservoir model. Inversions are then mapped into flow properties using calibrated relations such as Archie's Equation. The coupled models can then be used to both verify and improve on the reservoir flow model, which improves its predictive power and utility as a management tool.

1345–1500
WEDNESDAY 21 FEBRUARY 2018

10D STRATEGY AND GEOLOGY MODELS

DYKES, SYNCLINES AND GEOPHYSICAL INVERSION – IS GEOLOGY IMPORTANT?

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In the past 10 years the average depths of cover for gold and base metal discoveries was 60 and 128 m respectively. Existing methods of geophysical search techniques appear to lose their practical effectiveness below 200 m. This lack of success has been highlighted as part of the general UNCOVER movement in Australia. A critical and thoughtful response requires not just handwringing, but careful improvements to the whole methodology of exploration geophysics. Clever methods, that do not work effectively, can mask this lack of success for a period. The original popularity of the magnetic method is revisited and suggestions are made for what works and what does not. New Airborne ElectroMagnetic 2.5D inversion technology promises to regularly reach to 500m in most terrains, and produce geological sections with marker beds, indicating the local folding and faults.

Gunn and Dentith (1997) list a variety of mineral exploration targets associated with magnetic minerals and discuss the use of aeromagnetic methods. This methodology is a good proxy for the traditional interpretation of potential field and other geophysical survey datasets and how they are often still used. With the passing of time, the record for finding deeper buried 'orebodies' by direct detection from magnetic datasets, with follow up drilling, has not been very successful. The average depths of cover for gold and base metal discoveries was 60 and 128 meters respectively (Schodde, 2017). It is obvious that the 'one size does fits all' approach will not work for all mineralisation types and mapping the geology remains critical to exploration success. Despite this, the temptation remains that the Tier One deposit that is the only target of interest, has more massive mineralisation so hunting the 'blob' will work! Experimental evidence indicates this is not so.

In the 20 years since Gunn and Dentith (1997) was published much change has occurred in the technology space, including desktop computing that far exceeds what could be previously imagined. This has not always been a blessing, as ineffective methods that appear to have merit have emerged and been given much more credence than might have been warranted.

This paper briefly examines some of the technology advances now available, and attempts an update on the Gunn and Dentith review paper, in the light of the actual performance in the last 10 years of exploration.

COMMON UNCERTAINTY RESEARCH EXPLORER UNCERTAINTY ESTIMATION IN GEOLOGICAL 3D MODELING

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3D geological models describe geological information in a 3D space using structural data and topological rules as inputs. They are necessary in any project where the properties of the subsurface matters as they express our understanding of geometries in depth. These models, however, are fraught with uncertainties originating from the inherent flaws of the modeling engines combined with input uncertainty. Because 3D geological models are often used for impactful decision-making it is critical that all 3D geological models provide accurate estimates of uncertainty. This research focusses on the effect of various structural input data uncertainty propagation in 3D geological modeling. This aim is achieved using Monte Carlo simulation uncertainty estimation (MCUE), a stochastic method which samples from predefined probability distributions that are estimates of the uncertainty of the original input data set. MCUE is used to produce a series of altered unique data sets. The altered

data sets are used as inputs to produce a range of plausible 3D models. These models are then combined into a series of probabilistic models as a means to propagate uncertainty from the input data to several final models candidates. The proposed talk will present new and more reliable sampling workflows for structural data along with innovative ways to reduce uncertainty using model clustering based on topological signatures and sensitivity analysis. The methods will be demonstrated on two synthetic cases and a real case (Yerrida basin model, WA).

MULTIDIMENSIONAL TOPOLOGY TRANSFORMS

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Most currently constructed 3D geological models are to a first order the result of transformations of:

- 1D (at the mine scale),
- 2D data (at the regional scale) or
- 3D data (when high resolution 3D geophysical data are available, such as in basins),

data into 3D.

The datasets used to project between dimensions vary according to the scenario, however they generally consist of a mixture of 0D observations and local temporal or spatial relationships (their topology). Modern software systems are able to use a sub-set of these relationships (fault-stratigraphy relationships for example) to build 3D geological models, however the relationships are not typically used as an independent constraint on how much of the 3D model is constrained by observations, and how much is generated by the end user (or the algorithms they use).

This study explores the relationships between topological observations in 1, 2 and 3D in order to better understand how these may be used in the future as inputs to a revised 3D modelling workflow. We have investigated both synthetic cases, where we have full control, and natural examples, which permit alternate hypotheses. This approach has potential relevance to mine-scale and regional 3D models where the 3D topologies are poorly defined by the existing data, but 1D and 2D constraints are available.

1345–1500
WEDNESDAY 21 FEBRUARY 2018

10E GEOPHYSICAL CASE HISTORY

AN ASSESSMENT OF GEOTEM, ZTEM, AIRMT AND FALCON SURVEYS OVER THE NEBO BABEL DEPOSIT, WESTERN AUSTRALIA

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The Nebo Babel Ni-Cu deposit was discovered in 2000 by Western Mining Corporation (WMC), then BHP Billiton and now Cassini Resources. Over this period, it has been the subject of extensive airborne geophysical investigations including Geotem, Falcon and more recently ZTEM, AirMt and Spectrem. Parts of the mineralised system respond well to the various airborne EM techniques, but the response overall is complicated by the presence of extensive paleochannel development. A combination of 1D, 2D and 3D processing techniques have been applied to the EM data so as to better understand the overall system responses and where possible, see if it were possible to separate the basement conductive response from that of the overlying Tertiary channels.

GEOPHYSICS FOR SEDIMENT HOSTED COPPER AND GOLD MINERALISATION, THE ROLE OF 3D IP

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Sediment hosted copper mineralisation involves redox precipitation of copper sulphides where oxidised basinal fluids interact with *in situ* organic material or migrated hydrocarbons. This is a common process in sedimentary basins so it is important to find fast and cost-efficient methods for their exploration. Airborne magnetic/ electromagnetic and ground gravity and electrical resistivity-induced polarisation (IP) methods are commonly used to explore for these types of deposits. The application of IP methods can be utilised as a direct targeting tool in the sediment hosted environment. Multichannel receivers, large transmitters, improvements in processing capacity has led to more confidence in inversion results and the recent popularity of the 3D IP technique. Examples of the application of large 3D IP surveys for sediment hosted copper deposits from Zambia and Alaska show that high grade copper mineralisation is associated with an IP response. Sedimentary textures associated with mineralisation compromise the inductive conductivity and resistivity response (anisotropy). An integrated exploration approach using geology, geochemistry and geophysics helps alleviate pursuing responses from digenetic pyrite, graphitic shales and specular haematite.

GEOPHYSICS OF THE PATTERSON LAKE SOUTH URANIUM DEPOSIT, SASKATCHEWAN, CANADA

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The Athabasca Basin's major uranium deposits and mines are generally proximal to graphitic conductors (reducing environment) and accompanied by an alteration 'halo' which is usually a resistive low, but can also be silicified (resistivity high). The sandstone environment is normally highly resistive, which makes things ideal for EM detection of weaker graphitic conductors at depth.

The Triple R deposit on Fission Uranium Corp's Patterson Lake South Property is located in Canada's Athabasca Basin, home to the world's richest uranium mines. The deposit is accessible by all-weather Highway 955, which continues north to the UEX-AREVA Shea Creek and to the Cluff Lake uranium mine. It is the only major, high-grade deposit in the region that is potentially open-pittable and is the largest mineralised trend in the region – currently standing at over 3 km in length.

The PLS discovery is chronicled from the initial airborne radiometric and EM surveys, to ground follow-up using DC resistivity and induced polarisation, horizontal loop EM, moving loop TEM and radon survey, leading up to the discovery holes.

The deposit shows excellent correlation with a VTEM conductive 'bright spot', an interpreted conductor and a resistivity low segment. Also significant is the evidence of cross structure seen in the resistivity at the west side of the displayed deposit outline.

The continued success of the resource delineation and expansion is attributed to the dedicated Fission staff for their work to bring the project forward. From discovery to resource estimate, the Triple R Deposit was achieved in just two years of drilling.

1345–1500 WEDNESDAY 21 FEBRUARY 2018

10F MAGNETICS

EXTENDING MAGNETIC DEPTHS PAST 1000 M

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Technology to characterise and differentiate multi-basalt flood events that are well separated in geological time, but subject to subsequent sedimentation and erosion in the sedimentary sequence, has been developed and applied in the NT. Extensions to this ongoing effort have been made to create optimised workflows, to present an interpreter with the weighted evidence both interactively, and also in pseudo-borehole logs, in the 3D context. A further extension is to modify the tuning parameters to look for deeper basalt flow-like targets.

Rather than continue with inefficient methods that require a super-computer to get the job done, engineering efforts have been made to make a tool that works simply and effectively on generic desktop computers.

By assuming that a TMI anomaly is due to layers of random dipoles, equivalent magnetic depths can be obtained from its power spectrum. The shallow limit is perhaps half of one flight spacing, above which the signal vanishes into noise.

Despite good S/N at the lower frequencies, the standard Fourier transform does not supply enough points to extract signal for depths much below twice the flight spacing. Intrepid is widening the window by changing the transform so that more points are available to estimate depths well below two flight spacings.

A demonstration assigns depths to the Derim Derim Dolerite, a marker in the Roper Group of the MacArthur Basin, assisting the tracking of the Velkerri Formation between boreholes.

USING AMS AND PALAEOMAGNETIC DATA TO ASSESS TECTONIC ROTATION: A CASE STUDY FROM SAVANNAH NICKEL MINE, WA

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In structural geology it is common to evoke shortening directions, which are assumed to apply to all rocks regardless of their rheology. This is not realistic. However, resolving the partitioning of strain is not straightforward, particularly for intrusive rocks, which tend not to develop visible tectonic fabrics, but act as rigid blocks which typically rotate to accommodate strain during deformation, rather than compress or shear. Unfortunately there are few methods that can be used to quantify such rotation.

Intrusions near Savannah Nickel Mine, East Kimberley, WA, were observed to have different deformation histories, despite being temporally equivalent. In this study we measured anisotropy of magnetic susceptibility (AMS) and remanent magnetisation in four intrusions. The observed K3 AMS vectors are typically normal to the magmatic layering in layered intrusions. Where K3 vectors sit along a great circle, the pole to that great circle indicates the rotation axis. Although original palaeomagnetic vectors needn't be normal to magmatic layering, they can be used similarly to test the consistency of the inferred rotation analysis.

The rotations inferred for the intrusions tested were consistent between the two techniques. Savannah and Savannah North, were subjected to N–S, NE–SW and NW–SE shortening, consistent with the Halls Creek Orogen. However, N–S shortening was dominant at Savannah and NE–SW dominant at Savannah North. Although Dave Hill displays evidence of NE-directed thrusting, later E-W shortening was dominant at both Dave Hill and Wilsons. Therefore, despite their equivalent emplacement ages and implied tectonic history, each intrusion has undergone very different deformation.

MAGNETIC FIELD SURVEYS OF THIN SECTIONS

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There is a significant challenge in trying to correlate bulk magnetic properties of rock bodies with their magnetic mineralogy. Magnetic responses of rock bodies are measured at different scales and reflect different attributes depending on the nature of the method. Bulk magnetisation is a vector sum of all the constituents, including direction and intensity of both remanent and induced components. New high-resolution ground and aeromagnetic surveys can measure bulk properties of bodies with increasing accuracy and very high sensitivity. To bridge the gap between magnetic surveys and detailed rock-magnetic measurements on mg-sized and 2.54 cm paleomagnetic core samples, we have developed a scanning magnetic microscope that produces magnetic maps over thin sections, or rock slices. These surveys can be performed in a field-free environment, so that only remanence is mapped, or alternatively (unique to our lab) magnetic fields can be applied in any direction. Therefore, we can map only the remanent component, or remanent plus

induced magnetisation. Such surveys allow direct comparison of the measured bulk-magnetic properties with the magnetic response of minerals in a rock sample. Case studies have been done to compare these thin-section measurements to larger-scale ground- and aero-magnetic surveys.

1345–1500 WEDNESDAY 21 FEBRUARY 2018

10G GROUNDWATER

GAINING INSIGHT INTO THE T_2*–T_2 RELATIONSHIP THROUGH COMPLEX INVERSION OF SURFACE NMR FID DATA

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One of the primary shortcomings of the standard surface nuclear magnetic resonance (NMR) measurement, called the free-induction decay (FID), is the uncertainty about the link between the signal's time dependence and the geometry of the pore space. Ideally, the FID signal's time dependence, described by the parameter T_2*, carries an intimate link to the geometry of the pore space, allowing robust estimation of pore-size and permeability. However, T_2* can also be strongly influenced by background magnetic field (B_0) inhomogeneity, which can mask the link to pore geometry. To improve the utility of surface NMR FID measurements, we investigate whether complex inversion of surface NMR data can be used to provide insight into the link between T_2* and T_2 (the parameter carrying the link to pore geometry). Synthetic and field measurements are presented to demonstrate that an alternative forward modelling approach that involves direct modelling of relaxation during pulse (RDP) effects can help constrain the relationship between T_2* and T_2. Complex inversions are performed using forward models that include RDP for varying magnitudes of B_0 inhomogeneity (consistent with observed T_2* values) and it is observed that satisfactory data fits can only be obtained given reliable B_0 distributions. Thus providing insight into the T_2*–T_2 relationship. Ultimately, we demonstrate that an alternative forward modelling approach may help improve the utility of FID measurements for estimation of pore-scale properties.

CONSTRAINED MAGNETOTELLURIC INVERSIONS FOR CHARACTERISATION OF COMPLEX AQUIFER SYSTEMS

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To investigate a key zone of hydrogeological interest, a 2D MT survey was carried out across the Badaminna fault zone, which is a basin-scale extensional fault system, running roughly North/South in the northern Perth Basin of Western Australia. The hydrogeology of the basin consist of a multi-level system of heterogeneous sedimentary aquifers and aquicludes. These aquifers supply the majority of water for Perth City. The Badaminna Fault separates aquifer systems of different salinity and age, and displaces both the Leederville and Yarragadee aquifers by about 500 m. The north-trending Darling fault separates the basin from the Archean Yilgarn Craton in the east, and thins towards oceanic crust in deep water about 150 km offshore, adding to the complexity of MT inversion.

Constrained MT inversions, using seismic, airborne EM and well logs, was able to define the electrical properties surrounding the Badaminna Fault zone as well as the hydrostratigraphy on both the eastern and western sides spanning a depth range from the near surface to more than five km. The near surface inverted MT electrical conductivities show good agreement with results from 1D inversion of AEM surveying. The MT inversion results moreover corresponds to resistivity logs from nearby wells. Based on the MT data salinity estimates were obtained for the deep portion of the Yarragadee aquifer, providing a better understanding of both the solute concentration and distribution of deep clay sealing formations.

A NEW GENERATION, PORTABLE, TIME-DOMAIN EM PROFILING SYSTEM

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Loupe is a new, portable time-domain electromagnetic system specifically designed for rapid reconnaissance and near-surface conductivity measurements. The receiver and transmitter are each carried by one person on a back-pack. Loupe incorporates a 3-component coil sensor with 100 kHz bandwidth, a fast-switching transmitter loop, a simple user-interface and the ability to navigate and recover position using RTK GPS. We believe that the ability to rapidly measure conductivity distribution in 3D in the near-surface using a rapid acquisition system will change how many geotechnical and mineral exploration programs are conducted.

We anticipate that the paper will present examples of data from a geotechnical investigation, an iron ore mine and a base metal sulphide deposit. Results will be compared against other techniques to illustrate the increase in near-surface resolution and speed of data collection.

1345–1500 WEDNESDAY 21 FEBRUARY 2018

10H GROUNDWATER

NOVEL METHODS FOR NEAR-SURFACE HYDROGEOLOGICAL FEATURE ENHANCEMENT FROM HIGH-RESOLUTION AIRBORNE MAGNETIC DATA

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The delineation of near-surface (0–300 m) hydrostratigraphy and tectonic features is essential for successful characterisation of groundwater systems and subsequent hydrogeological modeling.

While most remote sensing of such systems is commonly achieved using high-resolution airborne electromagnetic data, validated by drilling data, and complemented by the use of terrain and multispectral data, it is shown that there is also a useful role for high-resolution magnetic survey data. Various filtering of gridded magnetic data, when image-enhanced and interrogated with other datasets, reveal features such as faults, dykes and other structures which may influence the distribution and movement of groundwater. One of the most useful enhancements of magnetic data is tilt, in which the range of data from ±90° acts as an automatic gain control to highlight both strong and weak source responses. While it is difficult to obtain accurate depth information from magnetic data, useful relative depth estimates can be obtained by using, for example, the Tilt-depth method, in which half the width between the ±45° contours of the tilt grid is a measure of the depth to source. These depth estimates can be calibrated, where possible, by comparison with other data. Dip directions of source contacts can be estimated by using the attitudes of multiscale edges, derived from the maxima of total horizontal derivative data. Examples of the utility of high-resolution magnetic data, in its complementary role, are presented for two groundwater assessment project areas – the Menindee Lakes region in western NSW and the Keep River catchment in the Northern Territory.

RECENT ADVANCEMENTS AND APPLICATIONS OF LOGGING AND SURFACE MAGNETIC RESONANCE FOR GROUNDWATER INVESTIGATIONS

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Enhancing groundwater investigations, nuclear magnetic resonance (NMR) geophysics allows direct measurement of hydrogen in pore fluids and characterisation of groundwater flow and storage parameters, including porosity, pore size, and permeability. In the field, NMR can be applied both downhole, with logging NMR tools, and non-invasively with surface NMR methods. We present recent technical advancements in logging and surface NMR, all of which are aimed to improve measurement flexibility, efficiency, and accuracy. These advancements include hardware development as well as adaptation of survey methodologies. We present applications of current logging and surface NMR technology from a range of international sites as part of practical groundwater investigations. Applications considered include characterisation of the vadose zone, determination of aquifer hydrogeologic properties, detection of hydrocarbon contaminants, and imaging of thaw water in artic environments.

IMPROVED GROUNDWATER SYSTEM CHARACTERISATION AND MAPPING USING HYDROGEOPHYSICAL DATA AND MACHINE-LEARNING WORKFLOWS

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The Australian machine-learning workflows apply fusion, clustering, and estimation operations to hydrogeophysical data for deriving hydrostratigraphic units (HSUs). Data fusion is performed by training a self-organising map (SOM) with these data. The application of Davies-Bouldin criteria to K-means clustering of SOM nodes determines the number and location of HSUs. Estimation is handled by iterative least-squares minimisation of the SOM quantisation and topographical errors. Two workflows provide 3D characterisation of HSUs (and related attributes) from different hydrogeophysical data (measured, derived, interpolated, and estimated values) sets.

In Workflow 1, the SOM learns to recognise relationships among a subset of borehole geophysical and hydrogeologic data. Using the data-fusion approach described above, the missing hydrological data are estimated using these learned relationships and HSUs determined at borehole sample locations resulting in a low lateral density and high vertical density spatial distribution. Variogram modeling of the regional field data and HSU estimates is undertaken to evaluate the spatial statistical structure of selected attributes.

In workflow 2, the learned relationships between borehole data and the more spatially extensive AEM conductivity model are used to estimate the key attributes and HSUs at a number of locations away from the borehole. The AEM conductivity profile at a number of random locations are mapped to the SOM network and estimation performed to arrive at a set of continuous HSUs with high lateral density and medium vertical density (based on m-layer modelled structure). Performance metrics and validation are used to test each step of both workflows.

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