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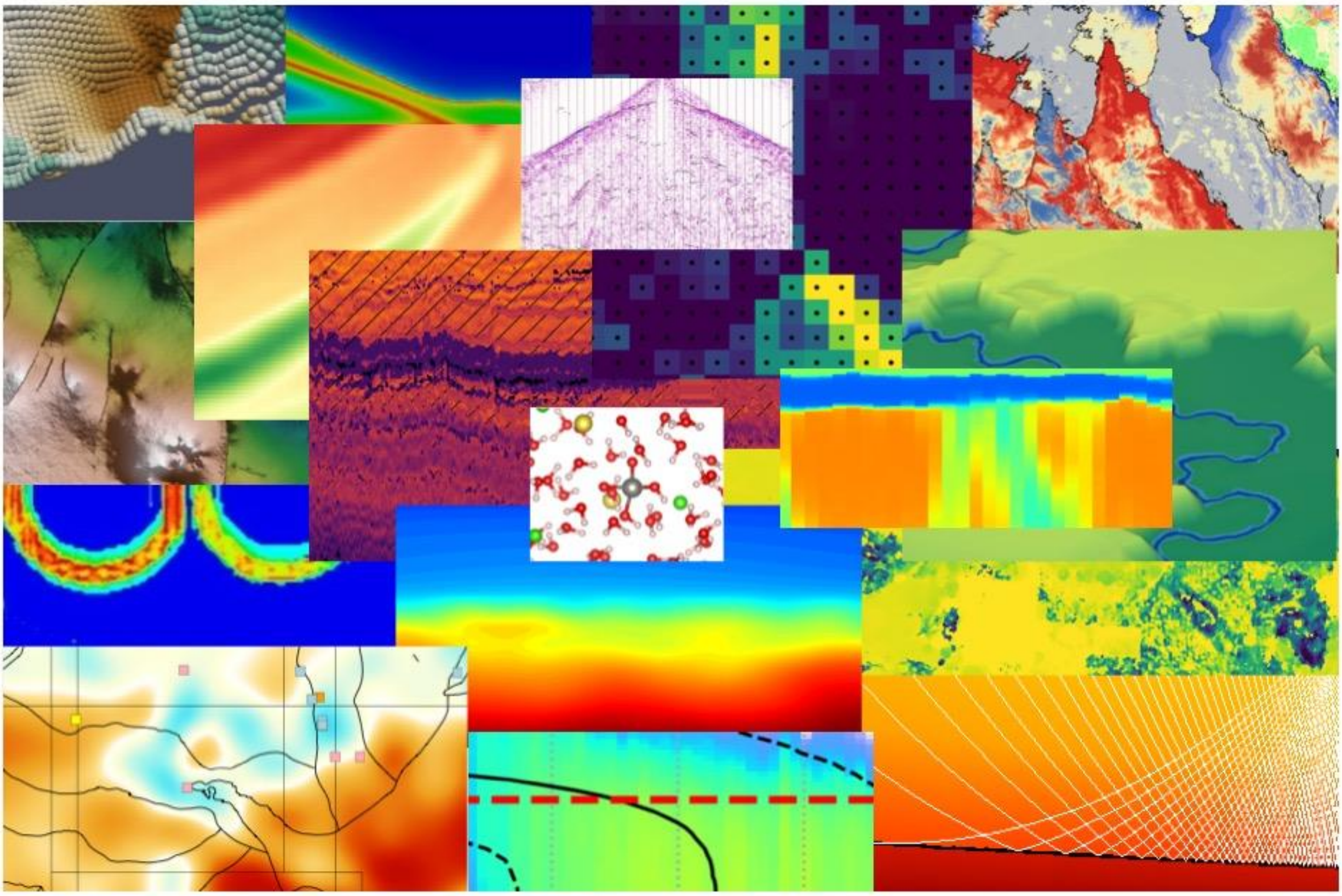
Subsurface 2020
The Inaugural Deep Earth Imaging Conference

The Optus Stadium, Perth | 12th - 13th February 2020



Contents

Director's foreword

Australia's future endowment of mineral, energy and water resources will come from far greater depths in the Earth. Onshore, this will be in settings where regolith and sedimentary cover characterise the landscape, not least because these materials cover ~80% of Australia's land mass. Our ability to find and develop these resources is limited by their complexities and their thickness. These challenges have been recognised in recent fora, and through the industry-led AMIRA Uncover Roadmap. The consensus view is that advanced geophysical, mathematical and computational tools are required, along with new geochemical and geological approaches/understanding to more precisely image the subsurface, to underpin our exploration concepts, and to predict processes that form these resources. An additional challenge, and opportunity, to those working in these sectors is a recognition that social and environmental constraints are now the norm. We need to work together to develop and secure our resource base in a sustainable way.

CSIRO's Deep Earth Imaging Future Science Platform (DEI-FSP) was created to contribute to the important national challenge of improving success in natural resource exploration in covered frontier terranes. Its formation recognised that a number of cross-disciplinary analytics and inverse method challenges impede development of new earth imaging tools and workflows. The Deep Earth Imaging initiative embarked on a unique opportunity to share concepts across multiple geoscience disciplines, and examples of that science will be presented at this meeting. Sub20 provides an opportunity to develop and extend the dialogue across disciplines around the themes of imaging, conceptualisation and prediction of water, energy and mineral resources. We are delighted to be partnering with academia, industry and government to facilitate dialogue on new ways to more precisely image and understand the characteristics of the subsurface, in turn unlocking the resource potential of a vast and relatively underexplored part of Australia.

On behalf of CSIRO and colleagues in the Deep Earth Imaging (DEI) Future Science Platform, it gives me great pleasure to welcome you to our inaugural interdisciplinary science forum - Sub20. Over the next few days we hope to challenge your thinking as what might be required to increase exploration success, for example by combining machine learning, forward modelling, inverse theory and predictive applications. We look forward to your participation

Tim Munday

Acknowledgements

CSIRO's Deep Earth Imaging Future Science Platform (DEI-FSP) would like to acknowledge the support of CSIRO's Science Council and Business Units, including Data 61, Energy, Land and Water and Mineral Resources. In particular, we recognise the contributions of our science cohort who help make the Platform what it is, and the underpinning efforts of many colleagues from the supporting business units. Finally, we would like to extend our thanks to you who are here today; to the presenters for their contributions and the audience who join with us to learn, discuss and progress the discussion in this valuable research space.

Thanks to you all for helping to make this a vibrant and exciting research environment.

Program overview

Day One: Wednesday 12th February 2020

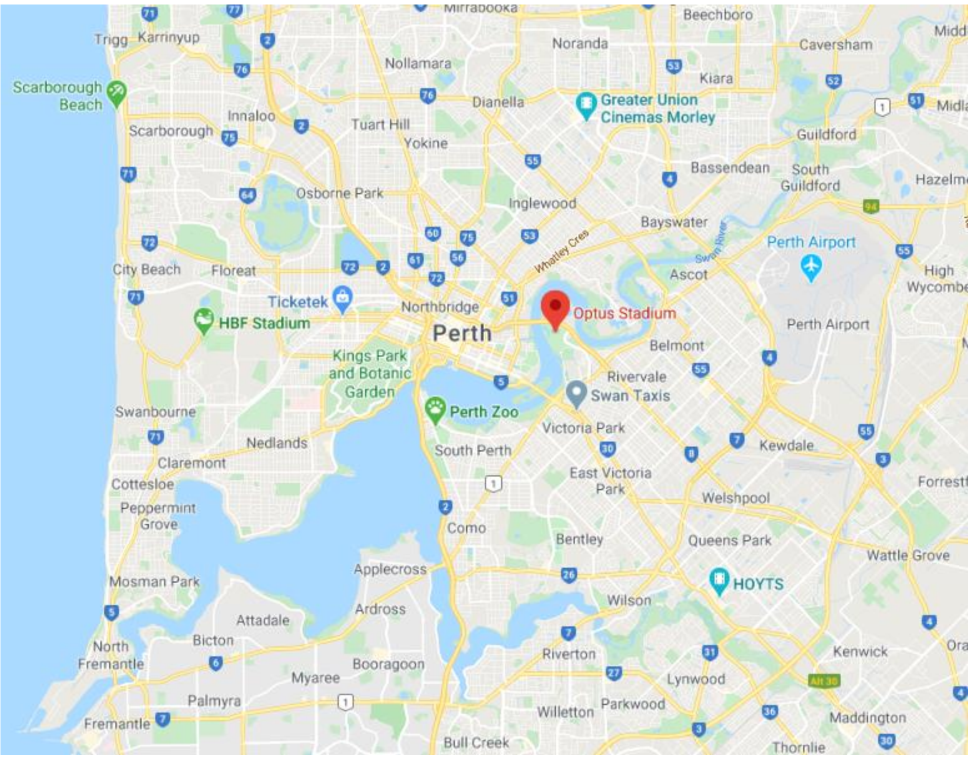
08:15 - 09:15	**Lobby Level 2 outside Cygnet Room** Registration	
09:15 - 09:45	**Black Swan Room** Welcome Introductions	
09:45 - 10:15	Keynote	
10:15 - 11:00	**Balcony between Black Swan and Cygnet rooms** Morning tea	
11:00 - 12:30	**Black Swan Room** Imaging I	**Cygnet Room** From models and images to concepts
12:30 - 13:30	**Victory Lounge** Posters & Lunch	
13:30 - 15:00	**Black Swan Room** Imaging II	**Cygnet Room** From models and images to concepts II
15:00 - 16:00	**Victory Lounge** Posters & Afternoon Tea	
16:00 - 17:00	**Black Swan Room** Round table discussions	
17:00- 18:30	**Victory Lounge & Platinum Terrace** Networking reception	
18:30	**Black Swan Room** Conference dinner	

Day Two: Thursday 13th February 2020

08:30 - 09:15	**Lobby Level 2 outside Cygnet Room** Arrive	
09:15 - 09:45	**Black Swan Room** Keynote	
09:45 - 10:30	**Balcony between Black Swan and Cygnet Rooms** Morning tea	
10:30 - 11:45	**Black Swan Room** Prediction I	**Cygnet Room** Current and new research initiatives
11:45 - 13:00	**Victory Lounge** Posters & Lunch	
13:00 - 14:00	**Black Swan Room** Prediction II	**Cygnet Room** Social licence to operate
14:00 - 15:00	**Victory Lounge** Posters & Afternoon tea	
15:00 - 15:30	**Black Swan Room** Keynote	
15:30 - 16:30	Panel Discussion	
16:30 - 16:40	Closing remarks	
16:40 - 17:40	**Victory Lounge** Closing reception & poster removal	

Venue

Sub20 is hosted at the Optus Stadium, Perth. The Stadium and the surrounding park is located east of the Perth Central Business District, on the Burswood Peninsula. With views of the Swan River and Perth city to the west and of the foothills to the east.



Getting to the Stadium

Public Transport: From Perth Station take the Yellow CAT bus from Wellingto Street/Plain Street Y30 (Stop Number 12912) to Waterloo Crescent/Wittenoom Street (Stop Number 16946) a 3 minute bus ride. Exit the bus and walk across the Matagarup Bridge to the Optus Stadium (distance 1.45 km).

Taxi/Uber/Ola: A taxi/Uber/Ola drop-off point is located within Marlee Loop, off Victoria Park Drive.

Car: Car parking is available within the Bus Station. To access parking, enter Roger Mackay Drive, off Victoria Drive and turn right at the roundabout. *Please note that parking surrounding the stadium is subject to availability and is not guaranteed*.

Getting to the Conference rooms – the Black Swan and Cygnet rooms

Enter through Gate D and proceed up to the Level 1 external concourse via the lift or staircase. Follow the concourse to the left and enter through Western Entrance 7 or 8. Once inside the Stadium, make a left turn, follow the internal concourse and take another left turn toward to reach the lifts. Take the lift up to Level 2. Follow the corridor straight ahead and enter either room via the internal hallway.

The conference is hosted across two presentation rooms, the Black Swan and the Cygnet rooms that are connected by an internal hallway and an external balcony with views over the stadium grounds. Morning tea and coffee will be served on the balcony. The Victory Lounge, located a short walk down a hallway from the Black Swan and Cygnet rooms, will host the posters, and be where lunch and afternoon tea are served each day. Clear signage and ushers providing direction, will be on hand to assist during the event.

Keynotes

Keynote 1 - Building models of the earth: merging methods, rock physics and geostatistics

Lucy MacGregor

Lucy is currently a principal at Edinburgh Geoscience Advisors Ltd, and CTO of Cognitive Geology Ltd. Prior to this, Lucy was the CTO of Rock Solid Images, leading the company’s technical group which specialized in the analysis and interpretation of seismic, well log and marine electromagnetic (EM) data and in the integration of these data types for improved reservoir characterization.

Lucy has a PhD from the University of Cambridge for research in the field of controlled-source electromagnetic (CSEM) methods and over 20 years’ experience in marine EM and multi-physics analysis for sub-surface characterisation. Following her PhD she was a Green Scholar at the Scripps Institution of Oceanography working on marine electromagnetic methods, before returning to Cambridge as a LeverhulmeTrust/Downing College research fellow. In 2000 she moved to the National Oceanography Centre, Southampton as an NERC research fellow to continue her work on marine CSEM methods, before co-founding OHM in June 2002 and joining the company as its CTO.

Building models of the earth: merging methods, rock physics and geostatistics

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Creating a robust image of the earth is a key step that enables the interpretation of geological processes, characterisation of sub-surface resources or prediction of sub-surface behaviour. Combining multiple geophysical approaches in the imaging and characterisation steps can lead to a more robust interpretation than if a single method is applied. For example, the integration of seismic attributes with controlled source electromagnetic (CSEM) data has been shown to dramatically improve the certainty with which commercial hydrocarbons can be distinguished from residual saturations (figure 1, [1],[2]), a problem that is hard to address with seismic alone. There are many approaches to multi-physics analysis and the choice depends on the data available, and the geological and/or geophysical goal of the analysis. A careful approach tailored to the study objectives and making use of a range of algorithmic approaches is required to ensure the best result.

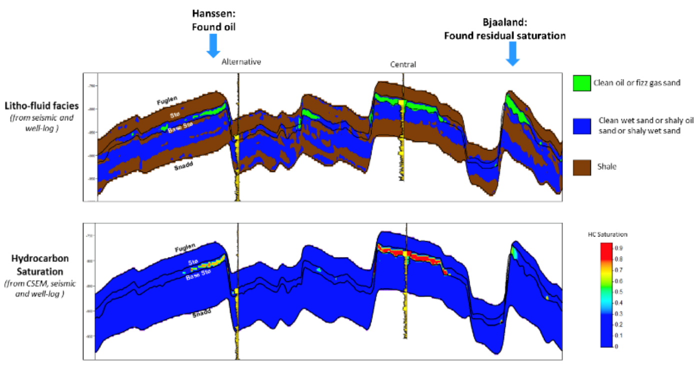

Figure 1. Multi-physics characterisation of a reservoir in the Northern Barents Sea (further details see [1]). Whereas seismically defined lithofluid facies can identify the presence of hydrocarbon, no distinction can be drawn between commercial and residual saturations. A multi-physics approach including EM data resolves this ambiguity.

Acknowledgement
The author would like to acknowledge former colleagues and Rock Solid Images (now owned by PGS) and current colleagues at Cognitive Geology for their input to the work presented.

References
Alvarez, P, Alvarez, A., MacGregor, L., Bolivar, F., Keirstead, R. & Martin, T., 2017. Reservoir property prediction integrating CSEM, prestack seismic and well log data using a rock physics framework: Case study in the Hoop area, Barents Sea, Norway.
Alvarez, P., Marcy, F., Vrijlandt, M., Skinnamoen, O., MacGregor, L., Nichols, K., Keirstead, R., Bolivar, F., Bouchrara, S., Smith, M., Tseng, H-W & Rappke, J., 2018. Multi-physics characterisation of reservoir prospects in the Hoop area of the Barents Sea.

Keynote 2 - Learning through inference: From Inversion to prediction

Malcom Sambridge

Malcolm Sambridge is a Professor in the Research School of Earth Sciences at the Australian National University. Since his Ph.D. at ANU in 1988 he has held post-doctoral positions at Dept. of Terrestrial Magnetism, in the Carnegie institution of Washington, D.C, USA, and at the Institute of Theoretical Geophysics, Univ. of Cambridge, UK, before returning to ANU in 1992.

His research contributions have been in geophysical inverse problems across the Earth Sciences and in particular seismology. His research interests lie in the development and application of techniques for geophysical inference; seismic wave propagation; imaging of the internal structure of Earth; robust inference from Earth science data; computational geophysics and numerical algorithms. In addition to research he has been involved in various ventures building research infrastructure and science outreach. In particular he has been part of a team building the Australian Seismometer is Schools network, a national outreach program installing instruments measuring the ground shaking of distant earthquakes in 50 high schools across Australia. He was awarded the Price medal of the Royal astronomical Society in 2009; elected a Fellow of the American Geophysical Union in 2010 and a Fellow of the Australian Academy of Science in 2015.

Learning through inference: from inversion to prediction

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Geophysicists want to learn about the Earth's interior from indirect measurements collected at or above the Earth's surface. All observations only indirectly constrain subsurface properties of interest, and so for the past 40 years geophysicists have created numerous methods to predict subsurface properties from surface observables. This field has become known as geophysical inverse theory. What is the future of this field given that we are now in the age of Machine Learning? Does a geophysicist abandon tried and trusted, and at times cumbersome, physics-based approaches in favour of the new panacea of data driven science, or does she reject the band-wagon and adhere to established algorithms based on well understood physical principles? Here we argue that neither should be the case. Rather the future lies in developing new creative ways to forge new subsurface imaging and prediction methods taking advantage of the power of both paradigms.

This talk will chart some aspects of geophysical inversion and how they might be related to and integrated with data driven science. A focus will be on future directions in geophysical inversion and where the biggest bang for buck might be achieved utilizing algorithms and insights from Machine Learning.

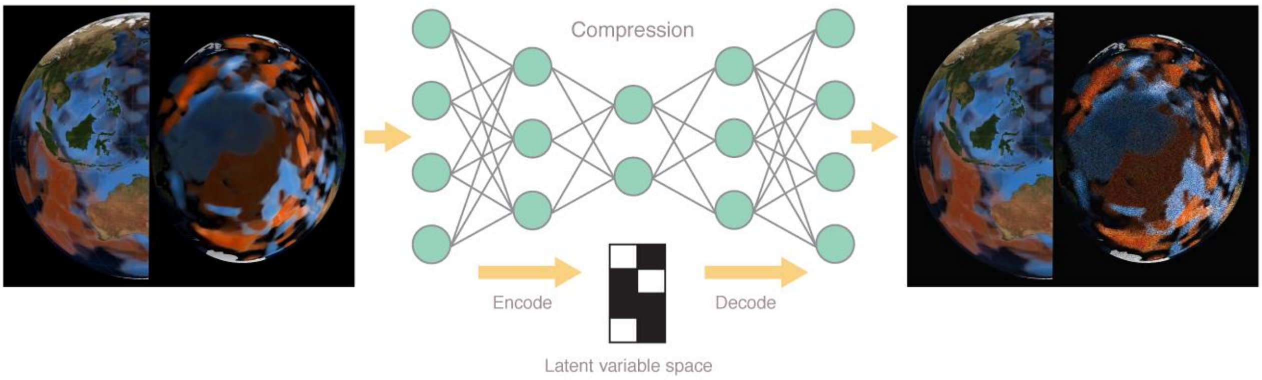

Figure 1. Conceptual illustration of how an Auto-encoder Neural network might compress a large scale 3-D model of the Earth into a latent variable space. The number of Latent variables would be much less than for the original Earth representation, but capture most of the significant features. Using such Machine learning tools it seems likely that large scale inversion problems could be projected into the much smaller latent space. However, is this cost efficient in general, and if it were, is the inverse problem in the latent space more or less difficult to solve than in the original parametrization?

Acknowledgement
Ongoing funding and collaborations are acknowledged with CSIRO, Future Science Platform for Deep Earth Imaging.

Keynote 3 – 'There and back again' … or, 'The mouses' dilemma'

Ken Witherly

Ken Witherly graduated from UBC (Vancouver Canada) with a BSc in geophysics and physics in 1971. He then spent 27 years with the Utah/BHP Minerals company during which time as Chief Geophysicist, he championed BHP's programs in airborne geophysics which resulted in the development of the MegaTEM and Falcon technologies. In 1999, Ken helped form a technology-focused service company that specializes in the application of innovative processing and data analysis to help drive the discovery of new mineral deposits.

'There and back again' … or,

'The mouses' dilemma'

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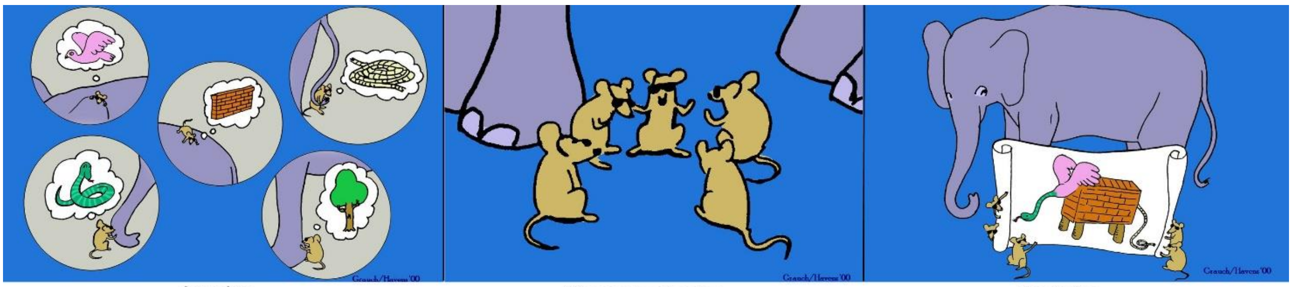
The Sub20 undertaking represents what could be considered as yet again the efforts by our geoscience community to develop the means to understand the subsurface whether for minerals, petroleum/gas, water and increasingly toxic materials often caused by anthropogenic activity. Now as then, the science and engineering being applied is the 'best of the day' and programs are well-funded and overall well run. Outcomes, however, have almost always fallen short of what was hoped for and after what seems like a mandatory period of silent reflection, the community organizes again to mount yet another expedition. What is suggested based on being involved with a number of such programs directly and having observed many others, is we forget that people need a vision and motivation to succeed that which transcends the pure technical challenges in front of them. The term 'silos' is often used to describe the barriers that are present and the importance of 'silo-jumpers' or 'silo-breakers' to the success of programs is grossly underappreciated. It is suggested that a program as complex as Sub20 consider the formal role for a project baird who can cross-link the people developing complex ideas to better be able to cross-convey their work to others through the use of traditional styles of communication such as song and poetry that have fallen out of favour.



Imaging *Conceptualisation* *Prediction*

Acknowledgement
T. Gauch/R. Haves/Tolkien

Full Program

Day One: Wednesday 12th February 2020

08:15 - 09:15	**Registration Lobby Level 2** Arrival tea and coffee - Hallway outside Cygnet room Poster setup - Victory Lounge	
	Black Swan Room - Welcome and opening address Chair: Tim Munday	
09:15 - 09:25	Welcome to Country	
09:25 - 09:30	Welcome to Sub20 - Tim Munday - *DEI FSP Director*	
09:30 - 09:45	Official opening - Cathy Foley - *CSIRO Chief Scientist*	
09:45 - 10:15	**Keynote - Building models of the earth: merging methods, rock physics and geostatistics** Lucy MacGregor - *Edinburgh Geoscience Advisors[1], Cognitive Geology[2]*	
10:15 - 11:00	**Morning tea** Balcony between Black Swan and Cygnet rooms	
	Black Swan room **Imaging I** Chair: Erdinc Saygin	Cygnet room **From models and images to concepts I** Chair: Clive Foss
11:00 - 11:15	*The past, present, and future of FWI at Woodside* Henry Debens - *Woodside*	*Conceptualising trapping frameworks and prospectivity trends using stratigraphic forward modelling* *Laurent Langhi - Energy, CSIRO*
11:15 - 11:30	*High-frequency full waveform inversion for subsurface interpretation* Troy Thompson - *DownUnder GeoSolutions*	*Developing models of Western Australia's lithospheric architecture: challenges and opportunities* Klaus Gessner - *GSWA*
11:30 - 11:45	*Joint facies/elastic full waveform inversion of seismic data* James Gunning - *Energy, CSIRO*	*Numerical simulation of critical mineral system geological processes* Peter Schaubs - *Mineral Resources, CSIRO*
11:45 - 12:00	*Monte Carlo simulations for model uncertainty and model automation* Edward Lewis - *PGS*	*Incorporating fault kinematics into implicit modelling* Lachlan Grose - *Monash University*
12:00 - 12:15	*Inversion of skeletonized seismic data by hybrid machine learning* Yuqing Chen - *DEI-FSP, CSIRO*	*We still need theoretical modelling* Thomas Poulet - *Mineral Resources, CSIRO*
12:15 - 12:30	Session summary	Session summary
12:30 - 13:30	**Posters** **Followed by lunch** Victory Lounge	
	Black Swan room **Imaging II** Chair: James Gunning	Cygnet room **From models and images to concepts II** Chair: Luk Peeters
13:30 - 13:45	*Magnetotellurics: past, present and future* Graham Heinson - *University of Adelaide*	*Map deconstruction helps model construction* Mark Jessell - *University of Western Australia*
13:45 - 14:00	*Guided inversion with Bayesian spatial ensemble fusion* Gerhard Visser - *DEI-FSP, CSIRO*	*Reconciling cover thickness estimates in Cloncurry Region in Queensland using Bayesian estimate fusion* Jelena Markov - *DEI-FSP, CSIRO*
14:00 - 14:15	*Gravity and magnetics for mineral exploration in the 2020s* Clive Foss - *Mineral Resources, CSIRO*	*Conceptualising geological Systems in 3D: Loop, the next Generation 3D Geological modelling open source package* Laurent Ailleres - *Monash University*

14:15 - 14:30	*Selecting optimal frequency range for estimating depth to magnetic sources* Stefan Westerlund - *DEI-FSP, CSIRO*	*Kinematic evolution model of intraplate rift margins: Dampier Sub-Basin* Patrick Makuluni - *University of New South Wales*
14:30 - 14:45	*Imaging across scales correlation wavefield* *Erdinc Saygin - DEI FSP, CSIRO*	*Chemostratigraphy in the Beetaloo Basin* Stuart Munday - *Chemostrat Australia*
14:45 - 15:00	Session summary	Session summary
15:00 - 16:00	**Posters** **Followed by afternoon tea** Victory Lounge	
16:00 - 17:00	**Round table discussions** Black Swan room	
17:00 - 18:30	**Networking reception** Victory Lounge & Platinum Terrace	
18:30	Conference dinner Black Swan room	

Day Two: Thursday 13th February 2020

08:30 - 09:15	**Arrival tea and coffee** Upload talks Hallway outside Cygnet room	
	Black Swan room Chair: Tim Munday	
09:15 - 09:45	**Keynote - Learning through inference: from inversion to prediction** Malcolm Sambridge - *Australian National University*	
09:45 - 10:30	**Morning tea** Balcony between Black Swan and Cygnet rooms	
	Black Swan room **Prediction I** Chair: Marina Pervukhina	Cygnet room **Current and new research initiatives** Chair: Tim Munday
10:30 - 10:45	*Rock typing for seismic inversion using rock physics models* Roman Beloborodov - *DEI-FSP, CSIRO*	*AusPass, making seismic data stewardship FAIR* Michelle Salmon - *Australian National University*
10:45 - 11:00	*Importance of rock physics for CO_2 geosequestration* Boris Gurevich - *Curtin University*	*Metal Earth: a multidisciplinary academic project using deep geophysical methods to understand localization of mineral deposits in Archean rocks* Richard Smith - *Laurentian University*
11:00 - 11:15	*Can surface geochemistry be used to identify and predict the crustal blocks of the Australian continent?* Hassan Talebi - *DEI-FSP, CSIRO*	*Deep learning for model emulation - an ML/AI FSP perspective* Dan Pagendam - *Data61, CSIRO*
11:15 - 11:30	*Applying machine learning to mineral exploration and geological mapping* David Cole - *Data61, CSIRO*	*New technologies for exploration and ore discovery* Yulia Uvarova - *Mineral Resources, CSIRO*
11:30 - 11:45	Session summary	Session summary
11:45 - 13:00	**Posters** **Followed by lunch** Victory Lounge	

	Black Swan room **Prediction II** Chair: Thomas Poulet	Cygnet room **Social licence to operate** Chair: Claudio Delle Piane
13:00 - 13:15	*Tungsten transport in ore-forming fluids: insights from ab initio molecular dynamics simulations* Yuan Mei - *DEI-FSP, CSIRO*	*Operationalising the Diamond Model of social license to operate* Hanabeth Luke - *Southern Cross University*
13:15 - 13:30	*Geochemical inversion of regional alteration assemblages for fluid compositions* Evgeniy Bastrakov - *Geoscience Australia*	*The role of earth science in informing policy and the regulatory process for mine approvals* Peter Baker - *Dept. Environment and Energy*
13:30 - 13:45	*What to do when probabilities are hard to believe: impact assessment using causal networks* Luk Peeters - *DEI-FSP, CSIRO*	*Offshore data acquisition. Enhancing the social licence to operate: challenges and opportunities* Simon Molyneux - *Molyneux Advisors Pty Ltd*
13:45 - 14:00	Session summary	Session summary
14:00 - 15:00	**Posters** **Followed by afternoon tea** Victory Lounge	
	Black Swan room Chair: Tim Munday - *DEI-FSP Director*	
15:00 - 15:30	**Keynote - There and back again…or The Mouses' Dilemma** Ken Witherly - *Condor Consulting*	
15:30 - 16:30	**Panel discussion - Imaging - Conceptualisation - Prediction** Lead: Tim Munday - *DEI-FSP Director*	
16:30 - 16:40	Closing remarks Tim Munday - *DEI-FSP Director*	
16:40 - 17:40	Closing reception & poster removal Victory Lounge	

Talks

Session - Imaging I

The past, present, and future of FWI at Woodside

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Full-waveform inversion (FWI) is a deterministic data-fitting procedure that seeks to generate high-resolution high-fidelity models of subsurface properties from pre-stack seismic data. Despite the numerical complexity and computational burden associated with FWI, since its original formulation by Lailly (1983) and Tarantola (1984), FWI has matured from the realm of academia to become a staple of seismic processing workflows in both exploration and exploitation settings.

For all its promise, however, the majority of FWI application across the oil and gas industry to-date has been to improve the shallow overburden in acoustic velocity models, with the aim of generating an improved image following migration. Principally, this is because FWI's original formulation – referred to here as classical FWI – is reliant on wide-angle forward-scattered measurements for generating long-wavelength kinematic updates to the macro-model. This has meant, in turn, that the success of classical FWI has been constrained strongly by acquisition geometry and geologic environment. This is not to say that, under the right circumstances, classical FWI cannot have a significant impact on business outcomes – with the change in volumetrics at the Atlantis and Scarborough fields being two of the most prominent public examples.

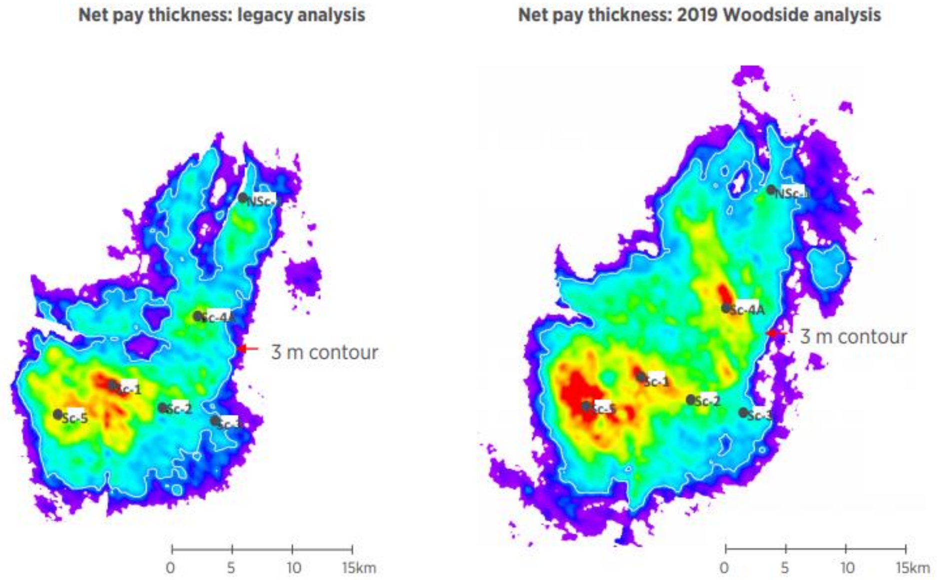

Figure 1. Change in recoverable resource (2C) at the Scarborough field following a systematic re-evaluation of the complete subsurface dataset (Woodside Energy, 2019). A key element in the re-evaluation process was the use of high-frequency FWI.

This presentation will explore the role that FWI has had at Woodside, focussing on some of the ways in which FWI technology has impacted the business (Fig. 1) and some of the ways that Woodside are working to evolve FWI such that it can fulfil its early promise. The presentation will cover aspects of algorithm design, data acquisition, and software deployment, while considering how these can be taken advantage of to get more-accurate images into the hands of interpreters sooner after acquisition.

Acknowledgement
The author would like to thank Woodside for permission to present this work.

References

Lailly, P., 1983, The seismic inverse problem as a sequence of before stack migration: Conference on Inverse Scattering, Theory and Application, SIAM, Expanded Abstracts, 206-220.
Tarantola, A., 1984, Inversion of seismic reflection data in the acoustic approximation: Geophysics, 49, 1259-1266.
Woodside Energy, 2019, Investor Briefing Day 2019, https://www.woodside.com.au/news-and-media/stories/story/annual-investor-briefing-day, accessed 8 January 2020.

High-frequency full waveform inversion for subsurface interpretation

Laurence Letki[1], Troy Thompson[1] and Matt Lamont[1]
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To improve our geological knowledge, we want to extract as much information as possible from our seismic data. Ever increasing compute power, in combination with better seismic data, enables us to develop better tools and to utilise better physics to build models of the subsurface. Full waveform inversion (FWI) is one approach which utilises the entire seismic wavefield to build a refined, high-resolution Earth model. Its use is well established as part of the depth model building workflow to improve imaging velocities. However, in this context it is often only the lower frequencies that are used.

High-frequency FWI attempts to utilise the entire seismic bandwidth to deliver an interpretation product in a reduced timeline. It combines velocity model building and imaging in a single step, by producing a migrated image (matching the amplitudes) imprinted on the velocity model (matching the kinematics). Arguably, this will outperform the combination of low-frequency FWI for velocity model building followed by least-squares reverse time migration (LS-RTM), which only images primary reflections modelled by the Born approximation. FWI uses a more sophisticated forward model with better physics and less approximations. But of course, the type of wave equation being solved is also a variable. Incorporating more physics within the FWI implementation combined with modern supercomputer facilities promises to increase the focus on very high frequency FWI in the coming years.

Through a series of field examples (Figure 1), we illustrate the meaning, applications and rewards of high frequency FWI in terms of qualitative interpretation. Quantitative interpretation is also considered with a comparison between the results of FWI and more conventional AVA inversion.

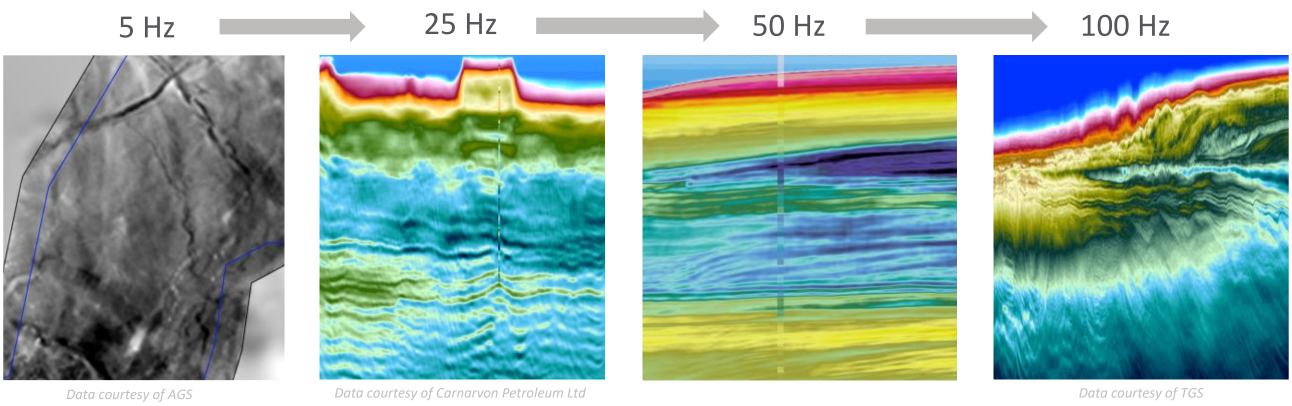

Figure 1. Example FWI models – from resolving shallow channels to improve imaging to producing high-resolution interpretation product

Acknowledgement
The authors would like to thank all geophysicists involved in the case studies included in this paper.

Joint facies/elastic full waveform inversion of seismic data

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Seismic Amplitude-Variation-with-Offset (AVO) inversion for elastic parameters jointly with litho-fluid discrete variables from migrated seismic data is now an established technique. Compared to conventional techniques based on adding smooth background models to impedance inversions, it has several advantages, including the ability to honour well-log data distributions, and directly image target fluids. These methods rely on Kirchhoff-style migrated images being "true amplitude", and are vulnerable to the presence of non-primary seismic energy such as mode conversions or multiples. In any deconvolutional style inversion such wave energy adds to the noise rather than the signal. To address this, it is possible to do joint elastic/facies inversion from shot records, using a full-wave modelling operation in the likelihood of a hierarchical Bayesian inversion, with optimisation performed using the expectation-maximisation algorithm. Since all wave energy is modelled, such a technique should theoretically have a higher S/N ratio than its AVO equivalent.

To illustrate, Figure 1 shows an example based on a flat, slab-like middle-east field with high impedance contrast (≈ 1.8) sequences of anhydrite, salt and limestone reservoirs. The seismic acquisition comprises shots and receivers along the top of the model. Inset (a) shows a simple 2-facies model mimicking this scenario, with scaled-down velocities but matching reflectivity; in (b) the high elastic contrasts cause standard Kirchhoff imaging methods to have serious amplitude balance problems, plus a strong coda from multiples. Inset (c) shows that standard joint facies-acoustic AVO inversion from this image is heavily infected by these artefacts. Inset (d) shows that using full-wave modelling, joint inversion can undo the effects of the multiple cascade and produce a balanced image without phantom reservoirs.

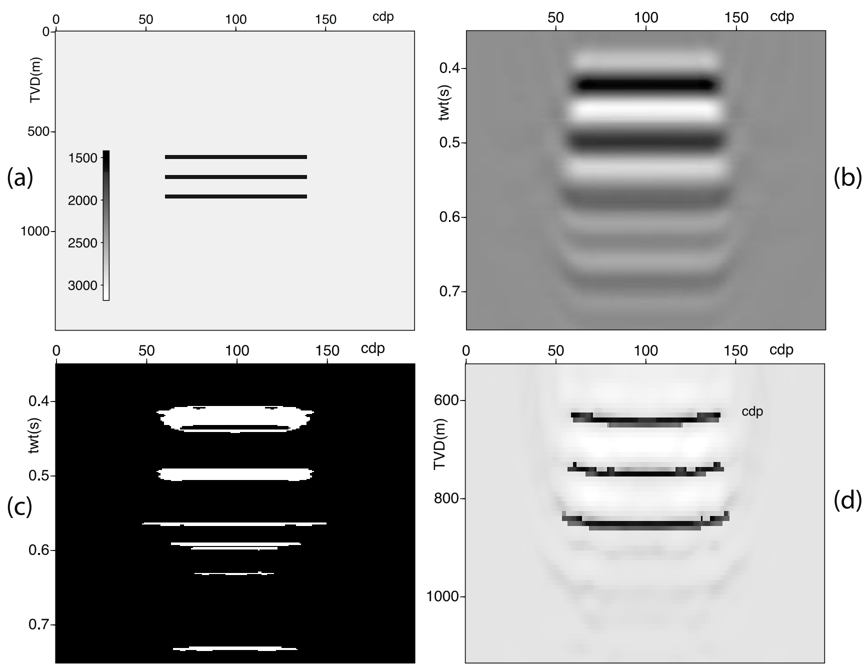

Figure 1. Example of joint facies-elastic imaging of high-contrast reservoirs. (a) true velocity model (b) Kirchkoff time-migrated image of bandlimited reflectivity (c) discrete {0,1} facies time image from AVO joint inversion, (d) velocity image from full-wave joint inversion; same scale as (a).

References
Gunning, J. 2019, Joint Facies/Elastic Inference in Waveform Inversion, in, Proc. EAGE Petroleum Geostatistics, Florence. https://onlinelibrary.wiley.com/doi/pdf/10.1111/1365-2478.12625.

Monte Carlo simulations for model uncertainty and model automation

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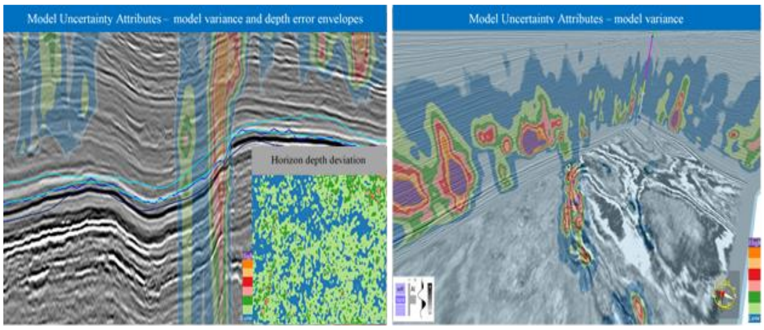

Figure 1. Examples from the Taranaki Basin, New Zealand (Lewis et al, 2018). Left shows the model variance along an inline. These variances and deviations can be mapped in 3D (right) to give a measure of uncertainty and risk.

The velocity model is a key component in effective reservoir evaluation; when used in the migration, it controls the spatial positioning of the seismic data. Typically, only one model is built and only one migrated seismic image is created. Auxiliary data may constrain the model and image, but they provide sparse uncertainty in the model.

To provide a measure of uncertainty, we use a Monte Carlo simulation (Bell et al, 2016); a method that enables an understanding of possible outcomes from a random population of inputs. The workflow produces attributes such as spatial positioning error bars. These metrics lead to an understanding of structural ambiguity and risk (Figure 1).

Pressure is mounting to reduce the turnaround time of seismic processing projects. As an extension of the model uncertainty workflow (Martin & Bell, 2019), we demonstrate an automated velocity model building tool that can accelerate Velocity Model Building (VMB), reducing turnaround time. We validate this approach on a data set, and compare results of this automated method with a model built in traditional way (Figure 2).

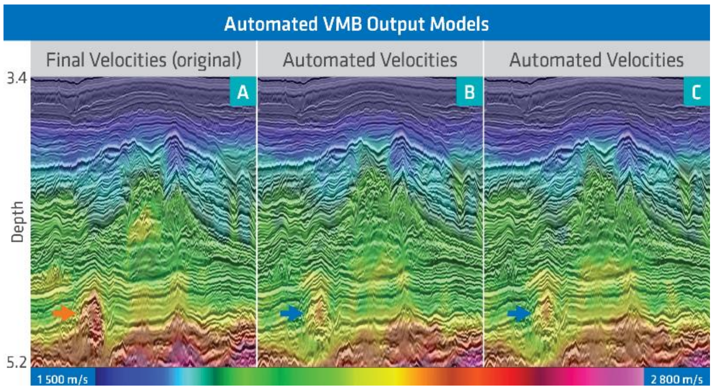

Figure 2. Automated VMB; panel A showing the final velocity model built in traditional waterfall approach, alongside panels B & C built from the automatic approach.

References

Bell, A. C, Russo, R., Martin, T., van der Burg, D., and B. P., Caselitz, 2016 A workflow to quantify velocity model uncertainty: 78th Conference and Exhibition, EAGE, Extended Abstracts, We P7 11.
Martin, T., and M. Bell, 2019 An innovative approach to automation for velocity model building: First Break, 37, no. 6, 57-66.
Lewis, E., Martin, T., Bell, A. C, van der Burg, D., and Russo, R., 2018 A Method For Assessing Earth Model Uncertainty In The Taranaki Basin, New Zealand: 1st Conference and Exhibition, AEGC, Extended Abstracts

Inversion of skeletonized seismic data by hybrid machine learning

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Full waveform inversion (FWI) has been shown to accurately invert seismic data for high-resolution velocity

models (Tarantola, 1984). However, the success of FWI relies on a good initial model that is close to the true model, otherwise, cycle-skipping problems will trap the FWI in a local minimum (Bunks et al., 1995). Simplification of the data by skeletonization reduces the complexity of the misfit function and reduces the number of local minima. One of the key problems with skeletonized inversion is that the skeletonized data must be picked from the original data, which can be labor-intensive for large data sets.

We present a hybrid machine learning inversion method, where the skeletonized representation of the seismic trace is predicted by an autoencoder neural network. The input to the autoencoder consists of the recorded seismic traces, and the implicit function theorem is used to determine the perturbation of the skeletonized data with respect to the velocity perturbation. The gradient is computed by migrating the shifted observed traces that weighted by the residuals of the skeletonized data, and the final velocity model is the one that best predicts the observed latent-space parameters. We denote this inversion strategy as a hybrid machine learning (HML) method because it inverts for the model parameters by combining the deterministic laws of Newtonian physics with the statistical capabilities of machine learning. Empirical results suggest that the cycle-skipping problem can sometimes be mitigated compared to the conventional FWI method by replacing the waveform differences by those of the latent space parameters. A significant novelty of HML is that it provides a general framework for using solutions to the governing PDE to invert skeletal data generated by any type of a rank reduction method, including principal component analysis and neural networks.

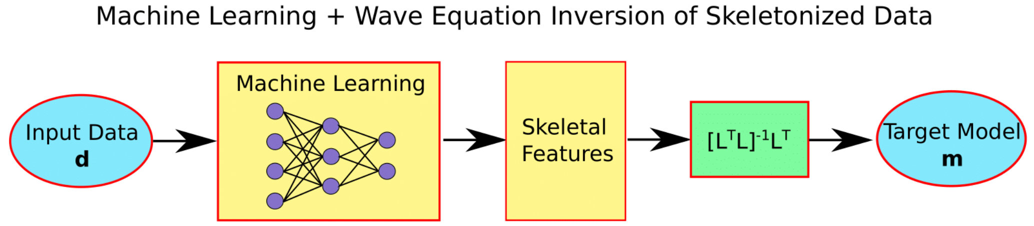

Figure 1. The strategy for inverting the skeletonized latent variables

Acknowledgement
Thanks to the Deep Earth Imaging Future Science Platform of CSIRO for funding and computing resources of CSIRO.

References

Tarantola, A., 1984, Inversion of seismic reflection data in the acoustic approximation: Geophysics, **49**, 1259-1266
Bunks, C., F. M. Saleck, S. Zaleski, and G. Chavent, 1995, Multiscale seismic waveform inversion: Geophysics, **85**, 1-61

Session – From models and images to concepts I

Conceptualising trapping frameworks and prospectivity trends using stratigraphic forward modelling

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Stratigraphic forward modelling (SFM) is a sedimentary process simulation that reproduces the development, transport and accommodation of sediment supply. SFM enables the prediction of lithofacies in areas where data are sparse, unevenly distributed, or at inappropriate resolution. It is particularly relevant in underexplored frontier sedimentary basins to reduce lithofacies distribution and architecture uncertainties. This approach is classically used to improve prediction of distribution and quality of lithofacies such as reservoir and source rocks in petroleum systems.

We used SFM to conceptualise the structural trapping framework and highlight hydrocarbon prospectivity trends in the Late Cretaceous marine and deltaic interval of the underexplored Ceduna Sub-basin. We sampled lithofacies, net-to-gross and shale volume distributions from a high resolution SFM over the Tiger and Hammerhead delta systems to evaluate reservoirs and seals juxtaposition patterns, quantify fault membrane seal and predict structural trapping opportunities.

The SFM for the Ceduna Sub-basin highlights a first order stratigraphic trend controlling the basin-scale reservoir and top seal prospectivity. It also predicts enough vertical variability within the sequences to create a wide range of stacked reservoir-seal couplets and to support local prospectivity from the central to the deeper offshore part of the sub-basin. We derived prospectivity trends from triangle juxtaposition diagrams and fault seal quantification performed on SFM dataset. These highlight a restricted WSW-NE prospectivity trend with the best reservoir and seal couplets in the Tiger and lower Hammerhead as well as a E-W prospectivity trend in the upper Hammerhead delta where thicker sand intervals are predicted, and structural trapping associated with juxtaposition seals and membrane fault seal is expected. Our conceptual trapping framework also underlines major risks for trapping potential in the central Ceduna, consistent with the findings at the nearby Gnarlyknots-1A dry well.

Acknowledgement
This work comprises part of the Great Australian Bight Deepwater Marine Program (GABDMP) a public-good research program led by CSIRO, and sponsored by Chevron Australia, with the data generated to be made publicly available.

Developing models of Western Australia's lithospheric architecture: challenges and opportunities

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The formation and reworking of continental lithosphere provides geodynamic context for hydrothermal fluid flow and magmatism involved in the formation of mineral and energy resources. One of the aims of the Geological Survey of Western Australia is to increase the knowledge of Western Australia's subsurface through the integration of geophysical, geological and geochemical data in 3D structural models. An important aspect in pursuing this aim is to develop the capability to build, manage, analyse and store 3D models according to GSWA quality standards and stakeholder needs, which represents a formidable challenge, as the workflow to generate 3D models involves data acquisition, processing, visualization, interpretation, publication and archiving. EIS-funded collaborative projects with leading research institutions complement GSWA's capabilities in data acquisition, analysis and modelling, form an important part of our activities. We present examples how the systematic acquisition and integration of geophysical, geological and geochemical data can reveal critical ties between crustal evolution and mineral deposits and explain why we support an open-source 3D stochastic modelling approach for the future of geoscience data integration.

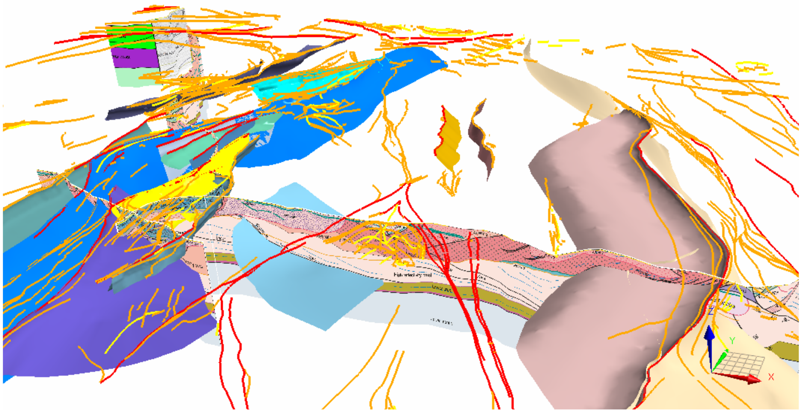

Figure 1. Screenshot from a 3D model of the Murchison Domain

Acknowledgement
We acknowledge the Western Australian Government's Exploration Incentive Scheme fur funding projects and activities related to the acquisition, processing, interpretation and publication of geoscience data.

Numerical simulation of critical mineral system geological processes

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The development of mineral systems involves the complex interaction between deformation, fluid flow, heat transport and chemical reactions. In order for geologists to test the influence of those processes and their interactions through "what if" scenarios, efficient simulation tools are particularly well suited. In particular, based on the Five Questions analysis for understanding mineral systems (Price and Stoker 2002), we know that understanding fluid flow is critical to the conceptual understanding of a system and advancing of our predictive capabilities. In this contribution we show how numerical simulation of hydrothermal ore-deposits provide an important tool for improving our understanding of fluid and other key processes which are active in mineral systems and for predicting the signatures of these deposits.

To do this we use numerical simulation at both ends of the hypothesis testing spectrum to cover: (1) the conceptual models to test singular fundamental physical behaviours of poorly-understood processes such as fluid flow through fault systems, or episodicity and periodicity related to deformation (Figure 1a) and (2) simulations incorporating multiple components (complex geometries, geological architecture, multi-physics, temperature and pressure dependent material properties, material property distributions) but with simplified underlying physics (Figure 1b). In this way we may account for a detailed understanding of a single phenomenon in some models or for more complex process interactions involving several phenomena but at a lower resolution.

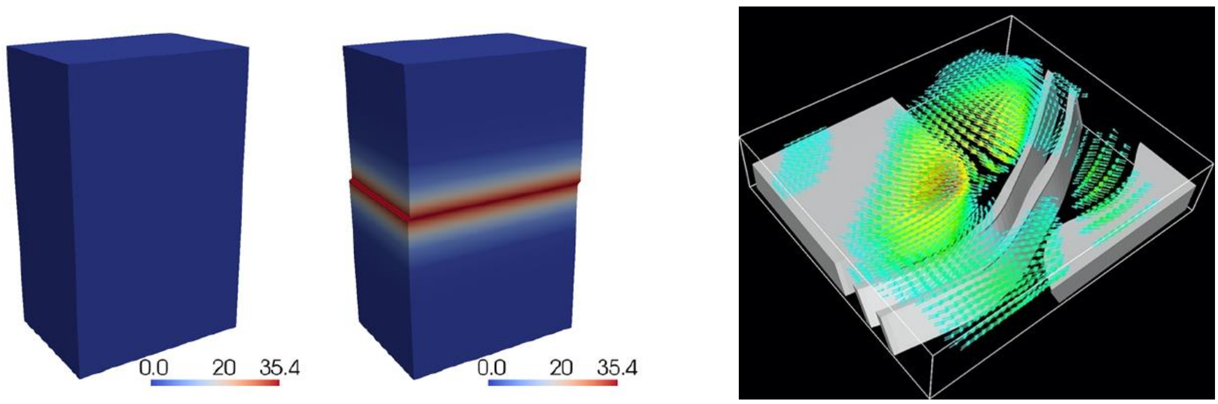

Figure 1. Examples of a) simple geometric simulations which focus on one detailed physical process and b) more complex geometrical models with coupling of a number of geologic processes

Currently we have the expertise to determine the necessary granularity and suitable inputs to the numerical models to capture the relevant driving process and test them with an adequate resolution (e.g. appropriate geometric complexity, number of geologic processes). To test tractable, identified hypotheses we welcome the opportunity to engage with industry to understand what geologic problems are critical for advancing their exploration efforts.

References

Price, G.P. and P. Stoker, 2002, Australian Geodynamics Cooperative Research Centre's integrated research program delivers a new minerals exploration strategy for industry. Australian Journal of Earth Science

Incorporating fault kinematics into implicit modelling

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Three-dimensional geological modelling is becoming increasingly important for resource management and exploration. This usually involves collating drill hole datasets, interpretive cross sections and level maps. Structural geology observations of folds and faults are usually poorly integrated with important information such as fault kinematics, fold axes, fold axial surfaces and vergence being difficult to directly incorporate into the surface descriptions. Recent developments for implicit modelling allow for direct incorporation of fold geometries by fitting periodic profiles to structural observations. This uses a curvilinear coordinate system that represents the finite strain ellipsoid of the fold (axial foliation and fold axis direction). Faults are more challenging to incorporate because they introduce discontinuities in the surfaces being modelled that are difficult to include in the surface description. There are two main approaches that are used for incorporating the fault displacement into surface descriptions: the first approach adds a displacement function (step function) into the mathematical description of the surface. Step functions do not capture fault kinematics and are only correct for faults where the fault is orthogonal to the layers being faulted. The second approach deforms an existing continuous surface using a kinematic operator to account for the fault displacement around a curvilinear coordinate system that is based on the fault surface, fault slip direction and fault extent. This approach is capable of using fault kinematics but requires the geometry of the surface prior to faulting to be known. Neither approach is capable of modelling the interaction between faults within complicated fault networks e.g duplex systems, flower structures and listric fault systems or modelling surfaces with complex pre-fault geometries such as fold series or intrusions where the wavelength of the fold or the volume of the intrusion, provide markers for testing the fault kinematics. In this study we propose an adaptation of the kinematic fault operator. Instead of applying the operator to an already interpolated surface, the fault operator is applied in reverse to the model area and geological observations. The model area is restored to pre-fault locations and the older geological surfaces can be interpolated within this space. The kinematic operator is added to the geological surface description allowing for the faulted surface to evaluated throughout the whole model area. We demonstrate these new developments to fault modelling using the new open source probabilistic 3D geological modelling package Loop3D on two synthetic examples: a faulted intrusion and a faulted fold series.

Acknowledgement
The Loop project is a OneGeology initiative, initiated by Geoscience Australia and funded by Territory, State and Federal Geological surveys (Australia and in-kind from Canada, UK and France), the Australian Research Council (ARC LP LP170100985) and the MinEx CRC.

We still need theoretical modelling

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Since its origin in the seventeenth century, the scientific method has proven its robustness and allowed considerable progress for mankind. Its iterative process is now very understood and is based on a never-ending succession of observations, model formulation and testing – experimentally or numerically – to (in)validate and refine hypotheses. With the exponential increase of data availability, there is currently an enormous focus on artificial intelligence/machine learning, which saw the development of new methods to surpass what was previously possible in many domains. On the back of such a successful approach, there is however a danger to sleepwalk through some of the other steps of the scientific method and in particular fall under the false impression than all underlying physical models are now well defined, with the only remaining tasks consisting in calibrating parameters.

In this contribution, we highlight the importance of pushing the research on physical models and showcase how theoretical work can lead to fundamental understandings in geomechanics, kickstarting the same scientific method as a result, only not from the modelling perspective rather than the more common experimental or observational angles. We focus on the periodicity of crack patterns in rocks under compression and investigate a recent theory [1] capable of explaining them with some purpose-built numerical tools. The high nonlinearity of the underlying partial differential equation indeed represents a challenge from the numerical point of view and a new stabilized finite element method [2] is introduced to overcome this issue (Figure 1). This technique allows us to explore a wider spectrum of solutions than those offered by classical finite element formulations, in order to analyse the influence of certain equation parameters in the solution behaviour, and devise physical experiments in the future to prove the validity of the approach.

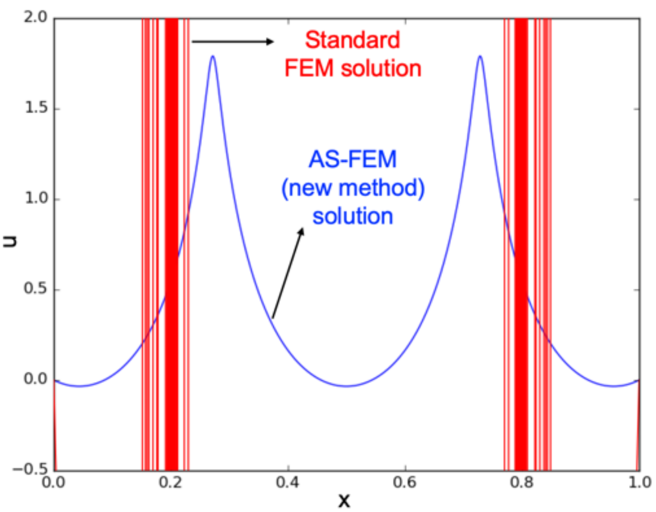

Figure 1. Comparison of numerical solutions using the new method and standard Finite Element Method.

References
Veveakis, E. & Regenauer-Lieb, K. (2015). Cnoidal waves in solids, J. Mech. Phys. Solids, 78, 231–248, doi: 10.1016/j.jmps.2015.02.010
Calo, V. M., Ern, A., Muga, I., & Rojas, S. (2019). An adaptive stabilized finite element method based on residual minimization. arXiv preprint arXiv:1907.12605

Session – Imaging II

Magnetotellurics: past, present and future

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The magnetotelluric method has been described over 70 years, but has gained significantly in popularity in the last decade. Of the approximately 4000 papers published using MT, almost half of these are from the last decade. There are two primary drivers for this change. Firstly, hardware and software have scaled up, such that >1000 site surveys are common, and massive 3D inversions tractable. Secondly, there has been a demand for deep-imaging, low-impact and relatively cheap resource exploration technologies in many diverse sectors.

Across Australia, from the 1970s-2000 the main approaches were large-scale grids using just the geomagnetic depth sounding (GDS) method to map regional-scale resistivity changes, and high-frequency MT for deposit scale exploration. After 2000, a number of transect MT profiles were additionally collected, often along reflection seismic lines to image crustal boundaries. In the last decade, the focus has shifted more to arrays, particularly with the start of the 55 km spaced AusLAMP long-period MT continental array in 2013, and various smaller broadband MT grids to resolve features from the AusLAMP array.

So what will be the trends for the next decade? As a personal reflection, the areas I see developing are:

- Cheaper instrumentation to increase a site density and data redundancy;
- Satellite inter-connected magnetic and electric field sensors (not necessarily co-located) for real-time data analytics;
- Co-deployment of MT and other geophysical sensors, particularly passive seismics and maybe also heat flow probes;
- Improved MT response estimation methods, particularly in areas of high-cultural noise;
- Rapid and approximate 2D and 3D inversions methods;
- Model analytics in terms of model uncertainty and inference;
- Incorporation of hard and soft model constraints from other geophysical and geological data; and
- Better geological interpretation of the geochemical, thermal and fluid-fluxes that have produced changes in resistivity to engage a wider non-geophysical audience.

Guided inversion with Bayesian spatial ensemble fusion

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Structural constraints and site-specific regularisation can guide inversion towards specific geologically realistic scenarios. When little additional information is available, the range of possibilities can be wide, making it difficult to formulate such informed priors.

We introduce a probabilistic geophysical inversion workflow for developing, visualising and testing multiple interpretations. First, Bayesian ensemble inversion is applied to small subsets of the available data using geometrically simple model parameterisations over small sub-regions with non-informative priors. The results of these separate uncertainty analyses are then used to build many candidate localised interpretations. Simple hypotheses about structures are then be formulated and applied to the sub-region ensembles using segmentation and filtering. Next, constraints for tying these partially processed sub-inversions together are formulated based on the results of the previous step. Bayesian spatial ensemble fusion is then used to combine the localised ensembles to form ensembles of larger 'fused' models. The results are then analysed to further refine the constraints and the process is iterated.

Instead of attempting to define a general-purpose regularisation/prior upfront, data is partially analysed in steps, with constraints being built up along the way where needed. This provides a highly flexible and way to include irregular data or hypothesis into the inversion process and to guide inversion towards realistic solutions. Key to making this possible is our Bayesian spatial ensemble fusion algorithm, which fuses ensembles of small models into ensembles of larger models in a way that approximates what would have been achieved by a more complex probabilistic inversion method. Computational expense was managed by developing various approximations and introducing a method to save and reuse expensive forward calculations. Our workflow is demonstrated with airborne electromagnetic and magnetotelluric data from Cloncurry Queensland. These tests show that our approach is able to shed light on complex posterior multi-modality and to clearly resolve resistivity boundaries.

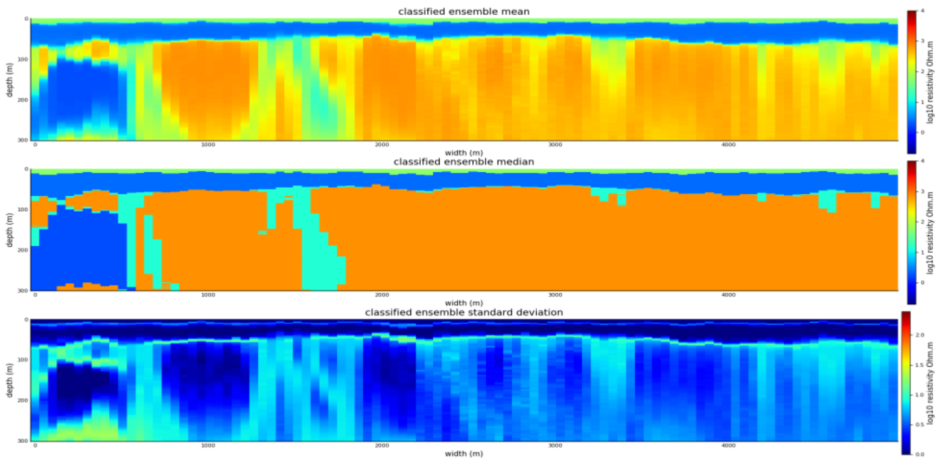

Figure 1. Posterior mean, median and standard deviation of an ensemble of 10000 fused resistivity models. These were derived from VTEM data collected in Cloncurry Queensland.

Gravity and magnetics for mineral exploration in the 2020s

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Aeromagnetic surveying is a crucial tool for mineral exploration, particularly in covered terrains that are so prevalent in Australia. The technology and methodology were substantially in place 70 years ago following developments in submarine detection in world war 2. There have been incremental advances with development of new magnetometers but only one revolutionary change with the advent of GPS navigation in the early 1990s. It was only after the introduction of differential GPS that high resolution surveys became feasible. Advances in data visualisation and computation have overwhelmed advances in instrumentation and are happening at an ever-accelerating pace. The 2020s are touted as the era for 'big data' and machine learning, with machine learning perhaps more likely to steal the show in gaining more from magnetic field data. Magnetic tensor gradiometry should also play a growing role through the 2020s.

Gravity meters have changed marginally over the last 70 years, but there was the revolutionary development in the late 1990s of airborne gravity gradiometry (coincidentally also arising from submarine warfare – in this case from the need for a submarine to move around the sea floor in stealth mode). AGG can be acquired together with aeromagnetics but it has had limited impact because at present few of these expensive surveys are flown. AGG has been an exciting field of instrument development, but sadly over the last few years three instruments in different companies and based on quite different methodologies have all failed at the commercial hurdle of high development costs and the technical challenge of achieving final break-through noise reductions. However, there are completely different advances in physics including MEMS and atomic interferometry which may provide the gravimeters of the late 2020s.

What we should look forward to in the 2020s are not just instrument-driven advances, but improved capabilities to recover more geological information from gravity and magnetic data. In large part this needs to come from strengthened understanding of the linkage between measured and simulated rock physics and gravity and magnetic fields. We have yet to realise the advantages of incorporating advanced petrophysical data into inversion studies or of better integrating potential fields and other methodologies. Most importantly to take gravity and magnetics beyond pretty image generation and push-button subsurface models we require improvements in geophysicists. Not long-ago Australia was a nursery for potential field geophysicists to work in mineral exploration around the world, but at present geophysics undergraduate courses are closing or at threat of closing, with few students coming into geophysics with strong mathematical and physics backgrounds. This threat to Australia's future in mineral exploration needs to be attended to.

Selecting optimal frequency range for estimating depth to magnetic sources

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The depth to the top of the deepest magnetic source is a proxy for the depth to basement under the assumption that basement is magnetic rock covered by non-magnetic sediment. Spectral domain methods allow for rapid estimation of the depth of magnetic sources from a magnetic anomaly map by analysing the power spectra calculated from a window of magnetic field data. The choice of an appropriate window size is critical when employing these methods, due to the trade-off between robustness and locality. Larger windows are desirable as they include more data to average out randomness and noise, and larger windows are needed to observe the low-frequency components which relate to the deepest sources. But they may also include multiple objects which can confuse analysis and spatially smear results, so smaller windows are desirable for improved spatial resolution.

The three properties typically estimated are the depth to the bottom of the layer z_b, the depth to the top of the magnetic layer z_t and the magnetic fractal parameter β, which describes how the magnetic source changes with scale. For our purposes we are not interested in the depth to the underside of the layer and consequentially can use smaller windows as we do not require the low frequencies to constrain the depth to the bottom of the layer. Hence the minimum window size is now limited by the expected depth to top of the layer.

A wide frequency range is critical to best separate the effects of z_t and β and obtain robust depth estimates. Above a certain frequency the spectrum is dominated by shallow sources and different types of noise; it no longer contains information about the deepest magnetic source. For a given window size we can obtain more robust estimates be carefully identifying this upper limit for the frequency range. The frequency at which the spectrum changes from being dominated by the magnetic layer to dominated by other sources can vary from location to location. Here we therefore introduce a methodology that selects a locally optimal upper limit for the frequency range by analysing the goodness of fit as a function of this frequency. For each location we identify candidate frequencies based on the R^2 value for a linear model for the power of the signal as a function of the frequency. From these candidate frequencies we chose the one resulting in the lowest root mean square error for the fitted spectral model.

We use synthetic tests to derive an empirical relationship between the recoverable depth to the top of the magnetic layer and the window size; and illustrate the degree of undesirable spatial smoothing caused by an unnecessary large window for a given recoverable depth. Recovered trends for the depth to basement for Australia are comparable to solutions obtained from different sources of information. The true value of our improved spectral method though lies in its suitability for application in a real-time environment due to its efficiency.

Imaging earth across scales with correlation wavefield

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Much of the effort over the past decade in the field of passive seismic imaging has focussed on using seismic ambient noise signals recorded simultaneously by seismic sensor networks, mainly utilising the surface wave component of the wavefield in seismic imaging. Meanwhile, some of the recent methodological developments enabled the use of body waves of the seismic correlation wavefield in earth imaging retrieved from the ambient seismic noise signals and also the scattered part of the earthquake signals.

I present some of the recent developments in the utilisation of the surface and body waves of the seismic correlation wavefield in earth imaging, using examples around the world including 4D monitoring of the earth. I also introduce a new interferometric wavefield reconstruction technique for improving the accuracy and volume of the measurements in earth imaging.

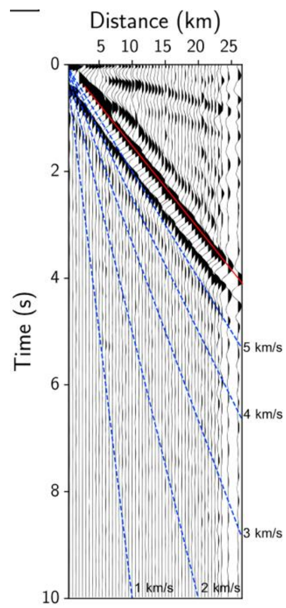

Figure 1. Extracted local body waves from the correlation of distant earthquake coda (Saygin & Kennett, 2019).

Acknowledgement
Yunfeng Chen, and Peng Guo, Leiyu He, Brian L.N. Kennett, Mehdi Qashqai are thanked for their various contributions to this work.

References

Saygin, E., and B.L.N. Kennett, 2019, Retrieval of Interstation Local Body Waves from Teleseismic Coda Correlation: Journal of Geophysical Research-Solid Earth, doi:10.1029/2018JB016837.

Session – From models and images to concepts II

Map deconstruction helps model construction

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Where available, the best predictor for the 3D geology of the subsurface is often the information contained in a geological map. This information falls into three categories of geometric data: positional data such as the position of faults, intrusive and stratigraphic contacts; topological data, such as the age relationships of faults and stratigraphic units, and gradient data, such as the dips of contacts or faults. In a 3D workflow, we combine all of these direct observations with conceptual information, including assumptions regarding the subsurface extent of faults and plutons to provide sufficient constraints to build a 3D geological model. Typically these conceptual assumptions are communicated via geological cross-sections supplied with the map, however these are often based on limited or no data. In the Loop Consortium we are developing algorithms that allow us to automatically deconstruct a geological map to recover the necessary positional, topological and gradient data as inputs to different 3D geological modelling codes. This automation provides significant advantages: it significantly reduces the time to first prototype models; it clearly separates the primary data from the data reduction steps and conceptual constraints; and provides a homogenous pathway to sensitivity analysis, uncertainty quantification and Value of Information studies.

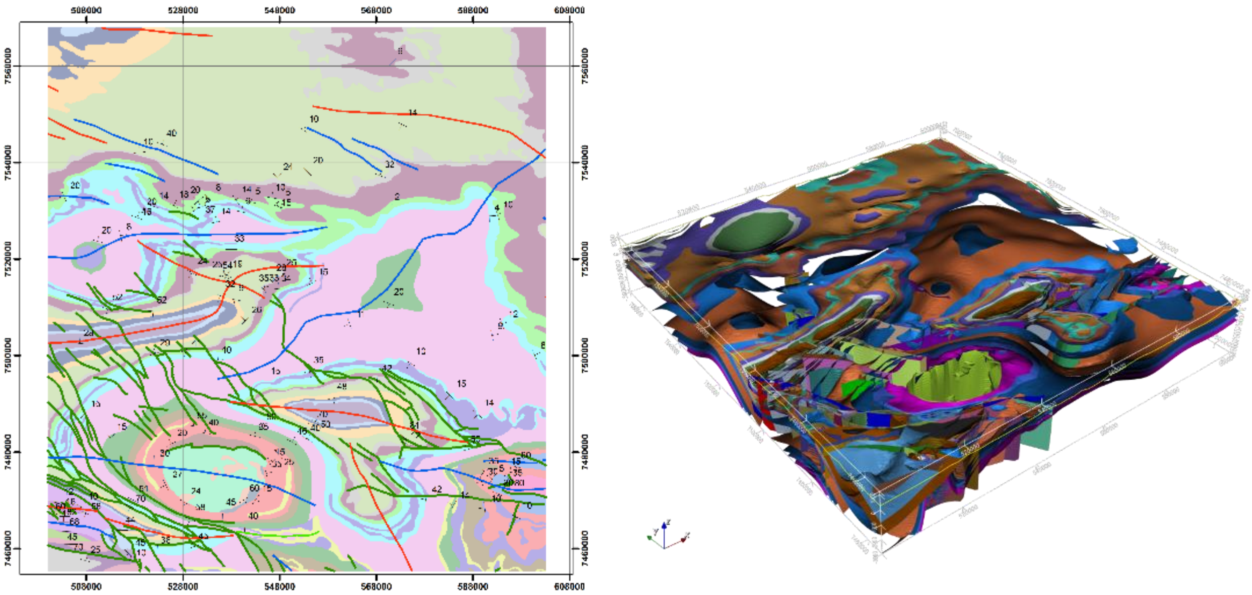

Figure 1. Left: Extract of the GSWA 500K Interpreted Bedrock Geology of the Mount Bruce area, Western Australia. Right: 3D Model built using only the information automatically extracted from the map.

Acknowledgement
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Reconciling cover thickness estimates in Cloncurry region in Queensland using Bayesian estimate fusion

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The Cloncurry region lies in NW of Queensland and includes the Mount Isa Inlier, one of the most highly endowed meatllogenic provinces in Australia, which has a long history of mining and exploration. The area is covered by the Jurassic-Cretaceous Carpentaria and Eromanga Basins sediments with the Mount Isa Inlier outcrops to the West and South. The fully concealed Millungera Basin underlies younger basins to the East. In order to de-risk further mineral exploration in this region it is important to know the thickness of cover. There is a variety of geophysical data available that can be used to estimate cover thickness. The point depth estimates of cover are derived from geophysical data using different inference methods. In order to create a map, these individual depth estimates must be reconciled/interpolated. The conventional interpolation methods do not produce the most optimal solution since these methods don't easily account for discrepancies in the geophysical data distribution, resolution of the data and consequently variable accuracy of the cover thickness depth estimates. Also, most of these techniques do not produce an uncertainty estimate of the result. We have developed a Bayesian estimate fusion (Visser and Markov, 2019) that accounts for the variable data inaccuracies of the point cover thickness estimates which produces a map of cover thickness and its uncertainty. Additionally, the method uses non-intersecting drill holes, which were not usually utilised to create a map of the cover thickness. The method deals with outliers, by differentiating between the point depth estimates related to the cover-basement interface and the false positives that might be coming from the intrasedimentary units or the deeper basement. Lastly, the method incorporates existing fault information which allows to better capture sharp cover thickness changes. The cover thickness and its uncertainty in the Cloncurry region are presented in Figure 1.

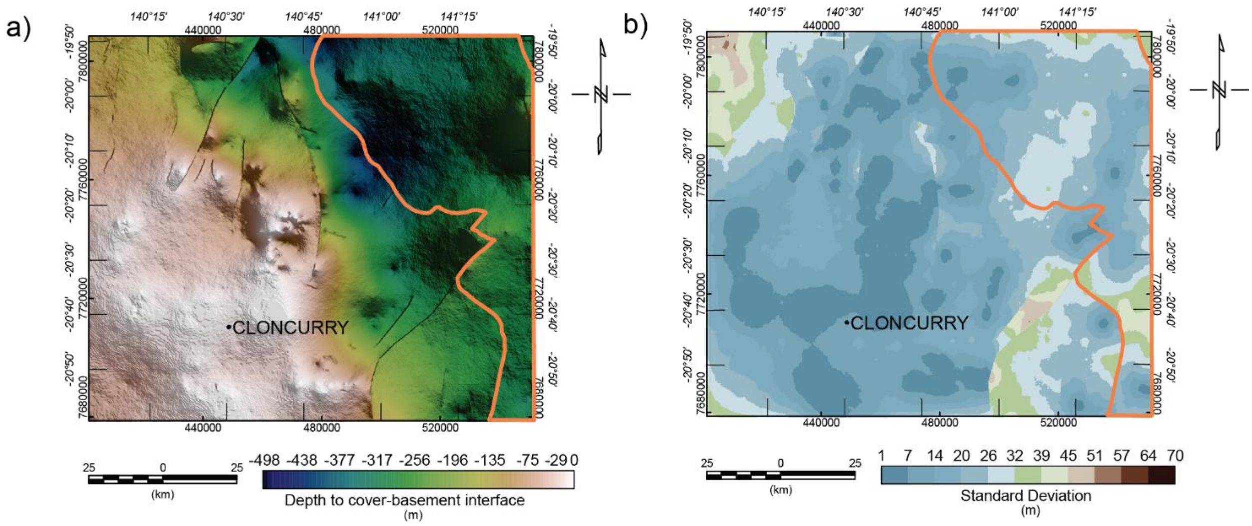

Figure 1. The cover thickness in Cloncurry. a) Map of the depth to cover-basement interface, b) Map of cover thickness uncertainty, expressed as the standard deviation of the ensemble solutions at each 200 m x 200 m pixel. Orange line is the boundary of the concealed Millungera Basin

References

Visser, G, and Markov, J., 2019, Cover thickness uncertainty mapping using Bayesian estimate fusion: leveraging domain knowledge, *Geophys J Int*, Vol.2019, Issue 3, p 1474 - 1490.

Conceptualising geological systems in 3D: loop, the next generation 3D geological modelling open source package

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With the current need for critical metals (including Cu), the ability to be predictive undercover and to improve mining of known resources, requires the ability to better predict sub-surface geology at multiple scales. Geologically consistent mine models should equate to better resource models and consequently a more economic way of producing the required resources for a greener future with increased recovery rates and reduced amount of resources required and waste produced. In exploration, the ability to predict sub-surface 3D geology and its uncertainty helps to optimise exploration programs, making them more efficient and more economical (financially and environmentally). We present the current state of "Loop" a new, multi-scale, open source, 3D geological and geophysical modelling platform that will enable field geologists to build geophysically and geologically integrated 3D geological models and assess and characterise the associated geological uncertainty.

To do this, we must enable:

- Easy data retrieval and input
- Better structural modelling, including all aspects of structural geology in poly-deformed terranes
- Better integration with geophysical inversions
- Characterise and mitigate uncertainty in geological models

We will present the overall modelling workflow with an emphasis on the structural modelling module as other talks at this conference will present the other steps of the workflow: Jessel et al.: data massaging and input; Grose et al., fault kinematics modelling; Giraud et al., Integration with geophysical inversions.

The outcomes of the project will be an open-source platform, available to the public, academia, industry and decision & policy makers; enhancing our societal capability in resources assessment, management and exploitation as well as geologically related environmental issues management.

Acknowledgement
The Loop project is a OneGeology initiative, initiated by Geoscience Australia and funded by Territory, State and Federal Geological surveys (Australia and in-kind from Canada, UK and France), the Australian Research Council (ARC LP LP170100985) and the MinEx CRC.

Kinematic evolution model of intraplate rift margins: Dampier Sub-Basin

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Plate reconstructions have relied upon magnetic data for the precise reconstruction of continents. From the Early Cretaceous onwards, magnetic seafloor isochrons are generally used and for the Paleozoic until the Late Jurassic paleomagnetic data is used. However, the method of reconstructing the earliest continental deformation prior to active rifting lack the same precision in positioning and large uncertainties exist in respect of the timing of the stages of deformation. This work aims at reconstructing the Intraplate rift margins of Dampier sub-basin in the Northern Carnarvon Basin, Western Australia. We employed a backstripping technique on 64 boreholes to produce sediment thickness maps of the sub-basin since 195 Ma. Thirteen isopach maps were created at different timesteps, showcasing the cumulative variation of sediment thicknesses over time. One of the results was the clear development of a central rift basin at each timestep. From this rift basin, we built a kinematic model of the evolution of rifting. The results indicate that initiation of rifting correlates with the Late Triassic Northeastern Gondwana Rifting, with the southern part of the rift opening faster than the northeastern region. Further rifting coincides with the 155 Ma Argo Ridge and the 136 Ma India-Ant-Arctica Seafloor spreading events. Rifting ceased in the Lower Cretaceous. Overall the rifting was dominated by lateral motion of both margins with the eastern margin majorly propagating at higher velocities than the western margin. This kinematic evolution impacts on the evolution of petroleum systems within the region by controlling maturation, migration, and trapping of hydrocarbons. This work presents a method that may be applied in other rifted regions to understand the evolution of rift basins for exploration purposes.

Keywords: Intraplate reconstructions, Rifting, Dampier, Backstripping, Isopach maps

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Chemostratigraphy in the Beetaloo Basin

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In the last few years elemental data have been gathered from a number of wells in the Beetaloo-McArthur Basin using both ICP-OES-MS and XRF techniques. These data are now available 'open-file' and Chemostrat have been using them to produce high resolution correlations (chemostratigraphy) for the Mesoproterozoic Roper Group Velkerri and Kyalla formations. The elemental data also provide information on the mineralogy of the formations, depositional environment and redox conditions. However, the data also present some signals that have been difficult to explain.

This paper will summarise the key elemental observations utilised for correlation as well as the characteristics of source-prone intervals, and the implications these have for the understanding of basin evolution. Figure 1 shows an example of XRF elemental data collected from Beetaloo W-1 [1]. A significant change in chemistry indicative of a shift in provenance occurs in the upper Velkerri Fm (the top of Sequence 1, Figure 1). It's possible to subdivide further into several packages, the chemistry in part reflecting the conditions necessary for the generation and preservation of high TOC source-prone intervals. These are characterised by relatively high silica, phosphorous, sulphur and calcium content, as well as being enriched with several trace elements, most notably molybdenum and uranium, in comparison to the interburden (Figure 1).

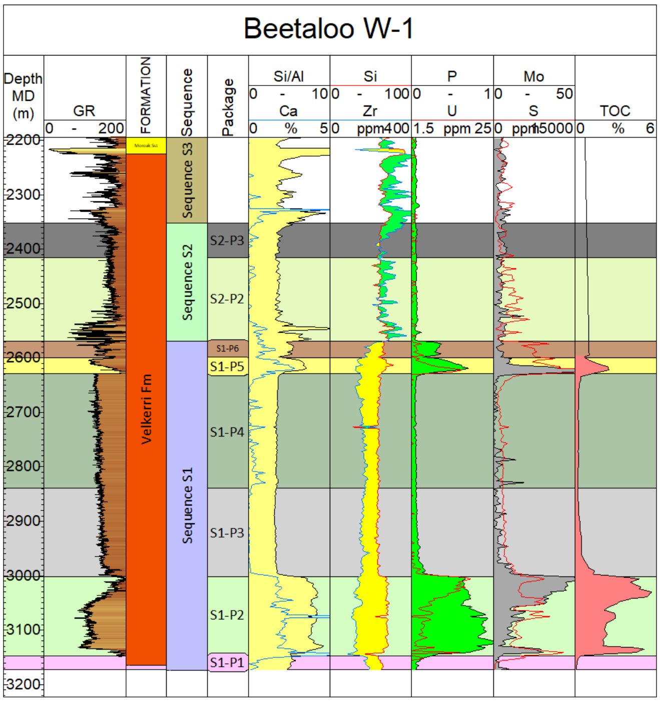

Figure 1. Beetaloo W-1 Elemental Characteristics of Velkerri Formation Source Rocks

References
Origin Energy Resources Ltd, 2016, Beetaloo W-1 Well Completion Report (Basic): GEMIS Report, **PR2017W004**, Appendix 5.

Session – Prediction I

Rock typing for seismic inversion using rock physics models

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Solving geophysical inversion problems involves supplying prior information to tackle non-uniqueness of the solution. Some advanced inversion algorithms require this prior in a form of statistical models that account for depth dependence of physical rock properties. But where do these models come from and how to identify their parameters objectively? Traditionally, identifying a suitable functional relationship between burial depth and rock properties among the plethora of possible models for each of the expected rock types in a subsurface formation is achieved by manually tuning the model parameters to satisfactory describe the borehole data in low dimensional data representations such as cross-plots. Here, instead, we present an objective and robust method that automatically identifies rock types from the borehole data by fitting models from rock physics model library and estimates the parameters of statistical model that are required in seismic inversion algorithms. We illustrate the performance of our method on a field data from the appraisal well in Satyr field offshore Australia (Figure 1).

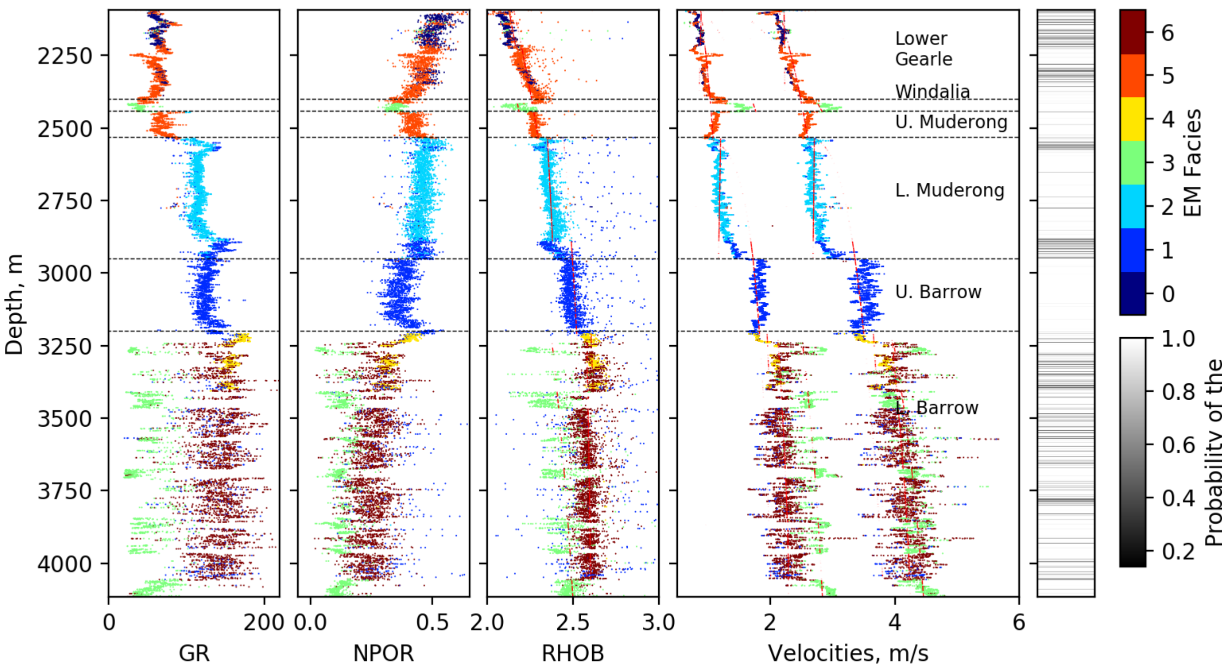

Figure 1. Results of automatic rock typing using Satyr-5 well data. Colour-coding represents different rock types identified by the algorithm. Dashed red lines illustrate corresponding rock physics model trends. Dashed black lines indicate formation tops from geological interpretation.

Importance of rock physics for CO_2 geosequestration

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Geophysics is an essential component of monitoring and verification for CO2 storage projects. In this context, rock physics relates geophysically measurable parameters (velocity, acoustic impedance etc) to rock and fluid properties, and is essential for forward modelling of the geophysical signature of injected CO2 and for quantitative interpretation of the geophysical observations.

CO2 is usually injected into the subsurface in supercritical form, and has density of a liquid but compressibility close to that of gas. The acoustic impedance of reservoir rocks partially saturated with CO2 is controlled by spatial distribution of CO2. When the distribution is spatially uniform, injection of a small amount of CO2 causes a sharp decrease of acoustic impedance, allowing detection of small CO2 saturation (on the order of 10%) by time-lapse reflection seismic method. However if saturation is heterogeneous, the seismic response is much less sensitive to small CO2 saturation. Poroelasticity theory predicts that at seismic frequencies the saturation can be considered uniform on the sub-meter scale, and this was the basis for predicting a significant reflection seismic response to a small (5,000 tonnes) injection of CO2 in the Otway experiment [1] – a prediction confirmed by field observations [2]. Modelling shows that CO2 injected into a depleted gas reservoir is unlikely to be detectable.

Quantitative interpretation of the geophysical response is challenging due to strong non-linearity of elastic properties as a function of saturation. However it is possible to map the CO2 plume body in 3D (parts of the reservoir with CO2 saturation above a certain threshold). Tests on Otway data show that seismic inversion coupled with statistical detection criteria gives a robust and contiguous plume image but leaves out parts thinner than 8m or with very low saturation [3]. Much smaller amounts (~15 tonnes) are detectable if CO2 is in gas form [4].

Acknowledgement
The Otway Project received funding through CO2CRC's industry members and research partners, the Australian Government under the CCS Flagships Program, the Victorian State Government and the Global CCS Institute. The authors wish to acknowledge financial assistance provided through ANLEC R&D supported by the Australian Coal Association Low Emissions Technology Limited and the Australian Government through the Clean Energy Initiative.

References
[1] Caspari, E., R. Pevzner, B. Gurevich, T. Dance, J. Ennis-King, Y. Cinar, M. Lebedev, 2015, Geophysics, 80, B95-B104, 10.1190/geo2014-0459.1
[2] R. Pevzner, M. Urosevic, D. Popik, V. Shulakova, K. Tertyshnikov, E. Caspari, J. Correa, T. Dance, A. Kepic, S. Glubokovskikh, S. Ziramov, B. Gurevich, R. Singh, M. Raab, M. Watson, T. Daley, M. Robertson, B. Freifeld, 2017, International Journal of Greenhouse Gas Control, 63, 150-157, 10.1016/j.ijggc.2017.05.008
[3] Glubokovskikh, S, R. Pevzner, J. Gunning, T. Dance, V. Shulakova, D. Popik, S. Popik, M. Bagheri, B. Gurevich, 2020, International Journal of Greenhouse Gas Control, 92, 102854.
[4] Tertyshnikov, K., R. Pevzner, 2019, B. Freifeld, L Ricard, and A. Avijegon, 2019, SEG Technical Program Expanded Abstracts, 4888-4892.

Can surface geochemistry be used to identify and predict the crustal blocks of the Australian continent?

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The Major Crustal Blocks (MCBs) of the Australian continent were defined based on the analysis of geological (e.g. outcrop mapping, drill hole, geochronology, isotope) and geophysical (e.g. seismic profiles, gravity, aeromagnetic, magnetotelluric) data. These blocks reflect distinct tectonic domains and can be used to improve targeting accuracy of surficial and deep natural resources. The National Geochemical Survey of Australia (NGSA project) consists of multi-element near-surface geochemistry of regolith overlying the major crustal blocks across Australia. This study explores the relationships between the surface geochemistry and the major crustal blocks of the Australia continent [1]. The compositional machine learning algorithms and geostatistical techniques were used to explore such complex relationships.

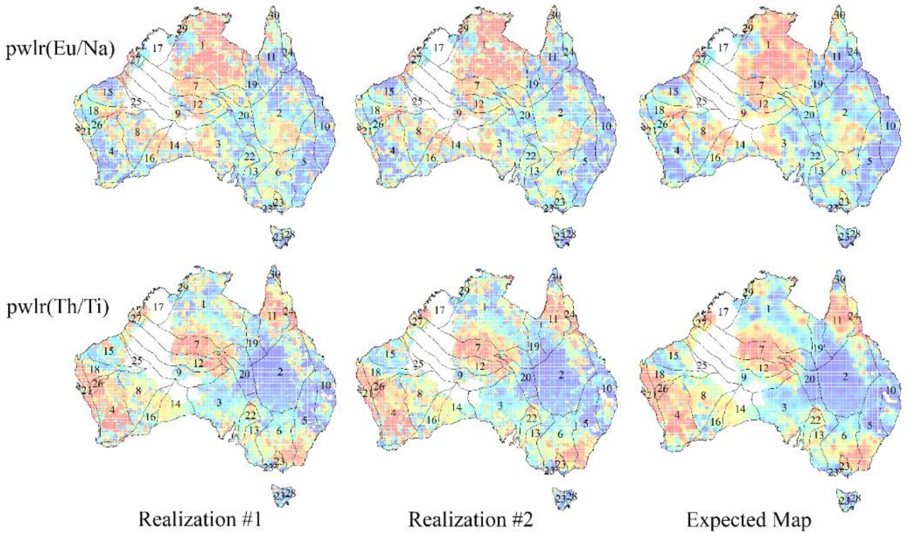

Figure 1. Simulated models for the most significant log-ratios associated with MCB #1 and #2 (warm colours are associated with high values)

Acknowledgement
I gratefully acknowledge the guidance, assistance, and support provided by Ute Mueller (Edith Cowan University), Raimon Tolosana-Delgado (Helmholtz Institute Freiberg for Resources Technology), Eric Grunsky (University of Waterloo), Jennifer McKinley (Queen's University Belfast), and Patrice de Caritat (Geoscience Australia).

References

Talebi, H., Mueller, U., Tolosana-Delgado, R. et al. 2019, Surficial and deep earth material prediction from geochemical compositions: Natural Resources Research, 28-3, 869-891.

Applying machine learning to mineral exploration and geological mapping

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The rate of new major mineral discoveries within Australia is decreasing as most deposits identifiable through existing techniques have already been found. At the same time the amount of available information relevant to mineral exploration is increasing. Machine learning (ML) techniques have the potential to address both these problems by incorporating all available data and identifying complex patterns not easily discernible by traditional approaches.

Such techniques can provide additional insight to geologists to complement their existing knowledge and expertise and can help inform better decision making. This talk will overview some examples of data-driven/ML algorithms applied to problems relating to mineral exploration, focusing on the analysis of public datasets in Queensland's North West Minerals Province. Examples include geological classification, geochemical prediction, and anomaly detection within interpreted geology models.

While these examples show the potential value of machine learning, also discussed are some common issues and considerations which arise when applying ML algorithms to geoscience problems. These include algorithmic assumptions, training data biases, model evaluation, and model generalisation/interpretation. An understanding of these issues, in conjunction with geological expertise, is required to derive meaning from ML outputs.

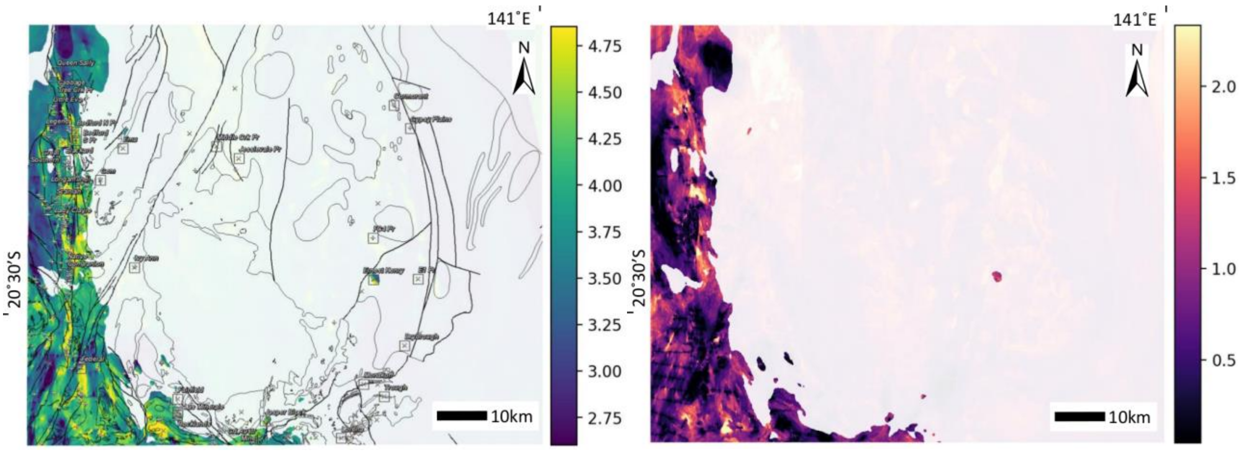

Figure 1: Machine learning model prediction (left) and uncertainty (right) of *log(Cu)* concentration using magnetics and gravity datasets.

Session – Current and new research initiatives

AusPass, making seismic data stewardship FAIR

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Since the inception of ANSIR in 1997 passive seismic data has been collected across Australia by Universities, State Geological Surveys and by Geoscience Australia (figure 1). Much of this data has sat on the shelves of those who have collected it, used for a specific project but not fully explored. Today the push for data to fulfil FAIR principles [1] requires that we dust off that data an make it available to all, providing the opportunity for the data to be further examined. AusPass is a new national seismic data server that will open up access to the rich data that has already been collected across the continent. The server is linked to the International Federation of Digital Seismograph Networks (FDSN) and to the Incorporated Research Institutes for Seismology (IRIS) making it findable to the national and international research communities. Metadata and data are accessible from the website www.auspass.edu.au and using programable FDSN web services. We are using community standard data formats that allow the data to be seamlessly integrated into programming routines making it fully interoperable. Allowing access to all means the data is reusable downstream for new studies and processing techniques. We hope that AusPass will foster and improve community research collaboration.

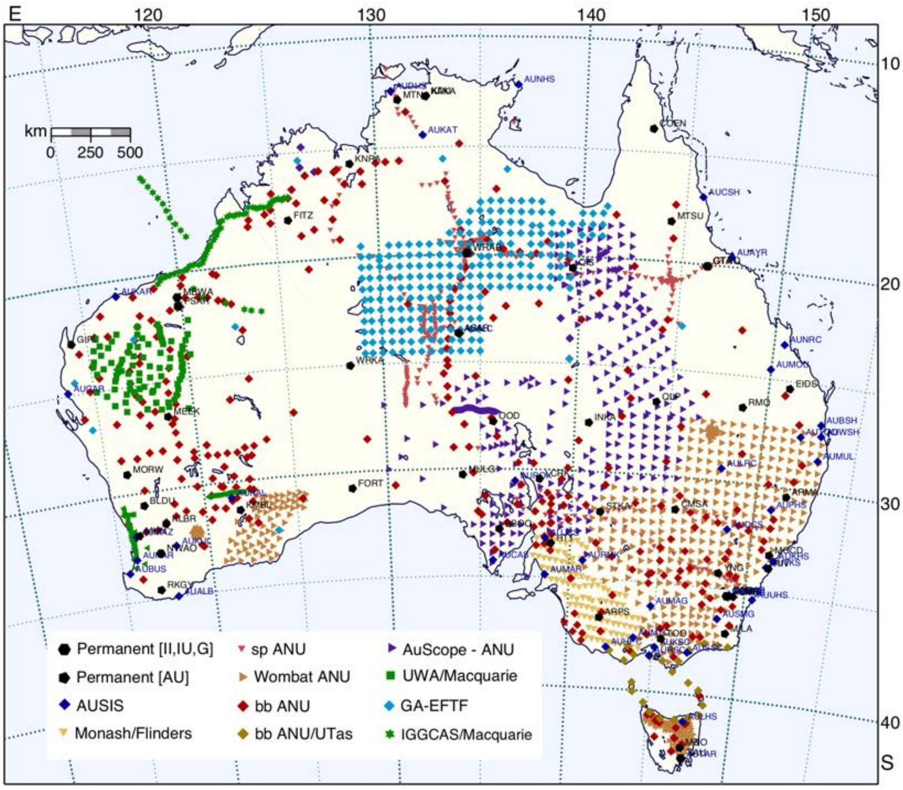

Figure 1. Current coverage of passive seismic data across Australia and the potential data for AusPass

Acknowledgement
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References

Wilkinson, M., Dumontier, M., Aalbersberg, I. et al. The FAIR Guiding Principles for scientific data management and stewardship. Sci Data 3, 160018 (2016) doi:10.1038/sdata.2016.
van der Hilst, R., Kennett, B., Christie, D., and Grant, J. (1994), Project Skippy explores lithosphere and mantle beneath Australia, Eos Trans. AGU, 75(15), 177– 181, doi:10.1029/94EO00857.

Metal Earth: a multidisciplinary academic project using deep geophysical methods to understand localization of mineral deposits in Archean rocks

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The main goal of the Metal Earth project is to improve the understanding of mineral endowment in Precambrian rocks. The focus is using new and existing geological observations, geochemistry, geochronology and geophysical data to compare differences between transects that cross metal endowed and lesser endowed Archean greenstone belts.

The new geophysical data collected include physical properties measurements on outcrop, hand-samples and in boreholes. Three types of active-source seismic data have been collected: regional reflection seismic data is intended to image down to the Moho; high resolution reflection seismic data were collected over some crustal scale structures associated with mineral deposits; and large offset refraction data were acquired in a few cases. The refraction data will be inverted using full waveform inversion methods, in the hope that some vertical changes in velocity can be identified at major structures. An experimental survey that acquired passive seismic data for a period of 40 days was tried on one of the transects. Regional broad-band magnetotelluric (MT) data have been collected on and around the traverses and higher resolution Audio MT data has been collected over some of the crustal scale structures. Finally, gravity data were acquired along the traverses. The regional reflection data showed strong sub-horizontal reflections in the mid-crust and below, while the high-resolution surveys were better able to image features in the top 10 km, including some of the crustal structures. Some vertical structures are evident on refraction data (so far processed using the first arrivals only). The MT data shows large and primarily horizontal conductive features in the mid crust and in many cases sub-vertical conductive features associated with crustal structures. The gravity and magnetic data is able to infer subsurface geometry in the upper crust when there are strong contrasts in density and magnetic susceptibility.

Acknowledgement
We acknowledge the Metal Earth project led by the Mineral Exploration Research Centre, Harquail School of Earth Sciences, Laurentian University.

Deep learning for model emulation – an ML/AI FSP perspective

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Activities like uncertainty quantification, typically require physical process models to be run many times. This ensures that the outputs of a model have taken into account potential uncertainties in parameters (parametric uncertainty), errors in data collection (measurement uncertainty) and uncertainty in process dynamics (structural uncertainty). Bayesian statistical approaches are routinely used to jointly quantify predictive uncertainties from all of these sources (Cressie and Wikle, 2011), however, they can be impractical when a model for a physical process has a very long run-time. Model emulation is one way to try and circumvent this problem. The idea is to model the computationally burdensome physical model with a faster surrogate model, referred to as the "emulator". An emulator is trained using data obtained from a set of model runs that are typically executed in parallel and may use different parameters and forcing variables.

In recent years, a number of modelling approaches have been used for model emulation. Gaussian processes have been popular since they naturally quantify the uncertainty in the emulator's predictions. However, their computational efficiency diminishes rapidly when the emulation dataset is large and this is often the case for complex models with many inputs and outputs. For this reason, first-order emulators (Hooten et al, 2011) that focus on the mean of the emulator's prediction have been advocated as an alternative solution.

In this work, we focus on how Deep Neural Networks can be used as model emulators in the environmental sciences and how these offer a number of major advantages. Firstly, these methods have good computational performance, even for large emulation datasets generated from models with many inputs and many outputs. Secondly, these models are easily structured so that they can provide a quantification of the emulator's predictive error, making them a competitor with Gaussian Processes. Finally, Deep Neural Networks seem capable of mimicking functions with sharp transitions or thresholds which we often encounter in physical models.

Acknowledgement
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References
Cressie, N. and Wikle, C.K. (2011). Statistics for spatio-temporal data. John Wiley & Sons.
Hooten, M., Leeds, W., Fietcher, J., and WIkle, C. (2011). Assessing first-order emulator inference for physical parameters in nonlinear mechanistic models. Journal of Agricultural, Biological and Environmental Statistics 16(4): 475-494.

New technologies for exploration and ore discovery

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New exploration techniques are currently being developed in response to decreasing ore discovery rate and increasing exploration challenges. The deposits that were exposed at surface have been mostly discovered, and we are now facing a challenge of exploring in buried environments. New technologies are being developed for more efficient and cheaper drilling to obtain samples, as well as for rapid and cost-effective analyses for informed decisions. These technologies include novel coil tubing drilling technology for mineral exploration in hard rock environments, portable or mobile analytical systems, and various down hole tools capable of collecting data while drilling or short time after drilling. Technology now enables us to communicate and analyse exploration results in real time which is transforming the way exploration will be conducted in the future. This talk aims to discuss how these new techniques can be integrated into more effective mineral exploration in deep, remote and covered environments.

Session – Prediction II

Tungsten transport in ore-forming fluids: insights from *ab initio* molecular dynamics simulations

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Tungsten is a strategic metal mined mainly from hydrothermal tungstate minerals in which the tungsten is in both tetravalent (e.g., tungstenite, $WS_{2(s)}$) and hexavalent (e.g., scheelite, $CaWO_{4(s)}$, and ferberite, $FeWO_{4(s)}$) oxidation states. To understand the transport of tungsten in ore-forming fluids and develop geochemical models for the formation of these deposits, we need reliable information on the speciation and thermodynamic properties of tungsten complexes in aqueous fluids over wide ranges of temperature, pressure and chemical composition. In the past four decades, there have been a limited number of experimental studies on W solubility and speciation in hydrothermal fluids (Bali et al., 2012; Redkin and Kostromin, 2010; Wesolowski et al., 1984; Wood and Samson, 2000; Wang et al., 2019). However, there has been no direct molecular-level study of the mechanism of tungsten complexation under hydrothermal conditions, and thus the role of chloride, sulfur and fluorine in aqueous tungsten species are poorly understood.

In this study, we used *ab initio* molecular dynamic (MD) simulations to calculate the speciation and geometries of tungsten W(VI) in chloride, sulfur and fluorine bearing brines up to 600ºC, 2kbar. We also used the thermodynamic integration method to also determine the acidic constants of tungstic acid, the stability constants of possible W(VI)-S and W(VI)-F complexes at temperatures up to 600 ºC. The derived thermodynamic properties enable better understanding and quantitative modelling of tungsten mobility in hydrothermal systems.

Acknowledgement
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References

Bali, E., Keppler, H. and Audetat, A., 2012, Earth Planet Sci Lett. 351-352, 195-207.
Moura, A., Dória, A., Neiva, A.M.R., Leal Gomes, C. and Creaser, R.A., 2014, Ore Geol. Rev 56, 73-93.
Wang, X.-S., Timofeev, A., Williams-Jones, A.E., Shang, L.-B. and Bi, X.-W. (2019). Geochim. Cosmochim. Acta 265, 313-329.
Wesolowski, D., Drummond, S.E., Mesmer, R.E. and Ohmoto, H. (1984). Inorganic Chemistry 23, 1120-1132.
Wood, S.A. and Samson, I.M. (2000). Economic Geology 95, 143-182.

Geochemical inversion of regional alteration assemblages for fluid compositions

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Understanding the distribution of alteration patterns is critical to assess the potential of a sedimentary basin to host base-metal deposits. Regular sequences of alteration zones can be used as vectors towards mineralisation and can constrain the compositions and sources of fluids. We offer a workflow for the inversion of empirical geochemical data to establish the compositions of hydrothermal fluids.

First, we run multiple 1D fluid infiltration models to predict results of water-rock interaction for a particular rock protolith (a “step flow through reactor model” by Shvarov et al., 2000). Model runs are completed for the same T-P conditions and vary only in composition of the initial fluid. Isothermal-isobaric conditions ensure formation of discrete alteration zones of constant mineralogical compositions. The output from the forward modelling is recalculated into the bulk chemical composition of the modelled rock.

Second, we identify clusters in empirical multi-dimensional geochemical data that might represent distinct alteration zones. We employ HDBSCAN (Campello et al., 2013), a clustering algorithm with a capability to identify arbitrarily shaped clusters and data outliers.

Third, we quantify how well the forward modelling predictions match the empirical clusters. For each cluster, we use kernel density estimation to create a probability function that allows us to quantify the likelihood of a predicted alteration zone to belong to the cluster. For each predicted alteration zone, we choose the most probable cluster. Given the individual likelihoods for each of the predicted alteration zones we compute a conditional likelihood to express the overall fit of the model to the data.

For a test case of the greater McArthur, characterised by extensive alteration of mafic rocks, the best performing models implicate potassium-rich fluids that might have resulted from either an evaporitic origin of brines or their interaction with felsic rocks prior to mobilisation of Zn and Cu from basalts.

References

Shvarov, Y. V., Zharikov, V. A., and Zhandarova , T. V., 2000, Calculation of an infiltrational metasomatic column on the basis of the local equilibrium principle: Geochemistry International, 38, 1041-1049.
Campello, R. J. G. B., Moulavi, D., and Sander, J., 2013, Density-based clustering based on hierarchical density estimates: Lecture Notes in Computer Science, 7819, 160–172.

What to do when probabilities are hard to believe: impact assessment using causal networks

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The use of probabilistic risk assessment is becoming ubiquitous in environmental impact assessment. The likelihood of an undesirable outcome is inferred through a combination of expert knowledge and historical data, often based on Bayes Law. This strong theoretical underpinning makes probabilistic risk assessment well suited to supporting scientifically robust decision-making.

However, a significant drawback to probabilistic risk assessment is that estimated probabilities are vulnerable to critique; the assessment is only as strong as its knowledge base. Estimating the probability of an unwanted outcome invariably and unavoidably requires a series of assumptions, such as the set of scenarios to include, the conceptualisation of the system, prior distributions of parameters and likelihood functions for Bayesian inference. For probabilistic risk assessment to be robust and trusted by decision makers and stakeholders, each assumption not only needs to be transparently justified, they also need to be clearly communicated as an integral part of the assessment.

For greenfield development situations, the existing knowledge base and historical information is often insufficient for a reliable probabilistic risk assessment. In the Geological and Bioregional Assessment (GBA) program, assessing potential impacts from unconventional gas development in the Cooper and Beetaloo GBA regions, we developed an alternative impact assessment methodology that focuses on possibilities, rather than probabilities.

The first step in the assessment is to develop a causal network that explicitly and systematically identifies all possible causal relationships between unconventional gas development activities and the environmental assessment endpoints. The causal network allows us to address the first question in the assessment:

1. *Is it **possible** that a change in state A will cause a change in state B?*

When there is no causal link between state A and state B in the causal network, the answer is ‘no’ and the causal chain to impact can be ruled out from the assessment. However, if we only considered the first question, the impact assessment would only consider a worst-case scenario. The second question we examine, for each cause –> effect pairs that are considered possible, is:

2. *Is it possible that a change in state A will **not** cause a change state B?*

The answer to this question is only positive when the change is unavoidable. In that case, the impact assessment focusses on estimating what the change in state B can look like. When it is possible to avoid a change in state B, the next question for the assessment is:

3. *Under what **conditions** will a change in state A cause a change in state B that exceeds threshold X?*

This question changes the impact assessment from a bottom-up approach, starting at the activity, to a top down scenario exploration, starting at the assessment endpoint. Spatially comparing the required conditions with the physical system and established control mechanisms allows the causal network to be refined and to prioritise causal pathways in informing decision makers.

To illustrate this workflow, we present a worked example of the potential impact of unconventional gas development in the Cooper GBA region on groundwater pressures and quality in deep aquifers.

Session – Social licence to operate

Operationalising the Diamond Model of social license to operate

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Social license to operate is a term that broadly describes social acceptance for a project, company or industry and its activities. Attempts to conceptualise levels of community acceptance led to the development of Luke's (2017)[1] Diamond Model of social license to operate, which extends Thompson & Boutillier's (2011)[2] model to include levels of, and processes involved in, social license withdrawal. While previous models conceptualise levels of acceptance principally in relation to community relationships with industry, the basic premise of the diamond model is that social license withdrawal relates to increasing levels of acceptance, approval and psychological identification with those who are actively resisting industry activities. This presentation will describe a number of ways in which the Diamond Model has been used to illustrate data arising from social license studies, in the context of both extractive industries and farming in New South Wales and Queensland, Australia. The model was first used in New South Wales to gauge levels of support and opposition to coal seam gas arising from an election-survey[1]; it was then applied to gauge levels of support for a horticultural industry using a councillor survey. Finally, it was used to illustrate changing levels of support for the coal seam gas industry by individuals from different stakeholder groups in towns and on the land, over seven years of a boom-bust cycle in regional Queensland[3]. The model is thus demonstrated as useful for application in a number of contexts, for illustrating individual and community-level perceptions of social license to operate at different points in time, and over time. Further potential applications are discussed and explored.

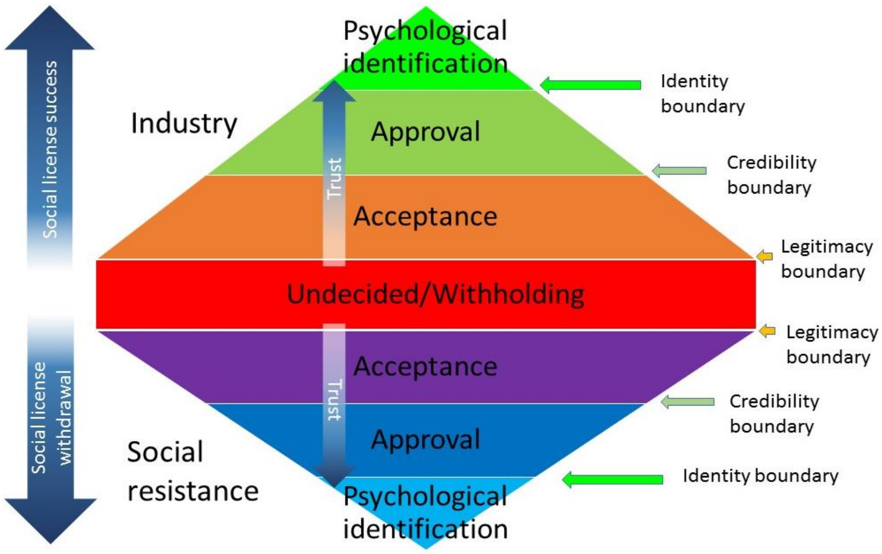

Figure 1. Luke's (2017) Diamond Model of social license to operate

Acknowledgement
My collaborators David Lloyd, Bill Boyd, Annie O'Shannessy, Mat Alexanderson, Kristen den Exter and Nia Emmanouil

References

Luke, H., 2017, Social resistance to coal seam gas development in the Northern Rivers region of Eastern Australia: proposing a diamond model of social license to operate: Land Use Policy 69, 266-280.
Thomson, I., Boutilier, R.G., 2011, Social license to operate. In: Darling, P. (Ed.), SME Mining Engineering Handbook. Society for Mining, Metallurgy and Exploration,Littleton, CO (pp. 1779–1796).
Luke, H., and N. Emmanouil, 2019, 'All dressed up' with nowhere to go: Navigating the coal seam gas boom in the Western Downs region of Queensland: The Extractive Industries and Society, in press.

The role of earth science in informing policy and the regulatory process for mine approvals

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Numerical groundwater models and their supporting geological, hydrogeological and ecohydrological conceptual models are sometimes the greatest 'sticking point' in the assessment and approval process of a project. Uncertainty in regards to the models robustness can lead to delays in regulatory decisions, resulting in model updates, additional data acquisition and, often, lengthy conversations. This leads to frustration both for the mine's proponent and the regulator.

Often the primary cause is the lack of geological (earth science) data and information which have been incorporated into these models. This leads to a high level of uncertainty in the predicted impacts, particularly to Matters of National Environmental Significance (MNES), which is often compounded by the use of deterministic numerical groundwater models.

Mining companies, quite rightly, invest heavily in proving up the resource to demonstrate an economic return. Less investment is forthcoming to obtain data that will inform impact modelling with companies wanting to gain approval to mine before spending on 'non resource' data which produces an additional tension in the approval process. This means that basic data such as hydraulic conductivity, both vertical and horizontal, particularly for aquitards, is limited or non-existent. Further, there is often limited assessment of potential cumulative impacts to receptors in an area.

Development of new, innovative and low-cost techniques is essential to overcome this issue to allow a quicker assessment and approval process with subsequent cost savings, not only for the proponent but to the public purse.

This presentation will highlight some of the common issues that slow the mine assessment and approval process and suggest key areas of focus for research in the earth science space.

Offshore data acquisition. Enhancing the social licence to operate: challenges and opportunities

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The acquisition of geophysical imaging data, in particular conventional marine seismic, in areas of shallow water (<20 m) has always been challenging in terms of cost, quality and permitting. A heightened sensitivity about the possible environmental impact of conventional marine seismic has made achieving environmental approval of marine seismic activity in water depths up to 60 m challenging in Australia.

In this abstract, a suggestion is made that the social licence to operate of offshore industries could be enhanced by re-framing permit work programs around in-permit mobilisations where impact to the exploration assessment is maximised, and environmental disturbance is minimised. This approach will be illustrated through a discussion of two case studies the Zenaide 3D and Bethany 3D seismic surveys and a consideration of alternative approaches from an environmental, work program and regulatory point of view.

Acknowledgement:
Updated from an extended abstract published in The APPEA Journal 2019, 59, 915-919

Posters

Combining edge enhancement images for more reliable detection of magnetic features

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The most common use of aeromagnetic data is the identification of magnetic bodies and geological contacts. To enhance an anomaly of interest, signal processing techniques are usually applied. This process is essential in areas where outcrop is limited, or the targeted anomaly is undercover. Nevertheless, the absence of geological information can make the interpretation of potential field data difficult since these methods have an inherent ambiguity. In order to improve the lateral detection of a source, it is recommended that one combines the output of several source edges detection algorithms. Since most enhancement filters use directional derivatives of different orders, it can amplify the high-frequency noise and compromise the noise-to-signal ratio. The workflow presented here allows the user to choose any combination of seventeen different filters and statistically stack the obtained results. The central point of this procedure is that locations with multiple solutions have a great confidence of representing a true edge while false peaks or mathematical artefacts will have fewer solutions and therefore can be easily disregarded. The algorithm was tested on both synthetic and real cases. The algorithm was able to correctly locate the lateral limits of the magnetic sources considered in all synthetic cases, regardless of the multiple sources' presence in the same area and the intense remanent component associated with them. The results obtained for the data contaminated by high frequency noise show an important characteristic: some individual filters present a better resolution than the combination them all. However, in real cases, it is not possible to know for sure the real shape of the magnetic source and, therefore, the statistical combination of different methods can lead to a safest interpretation. The algorithm is limited by the resolution of the data and the necessity of significative contrast on magnetic susceptibility along the geological features.

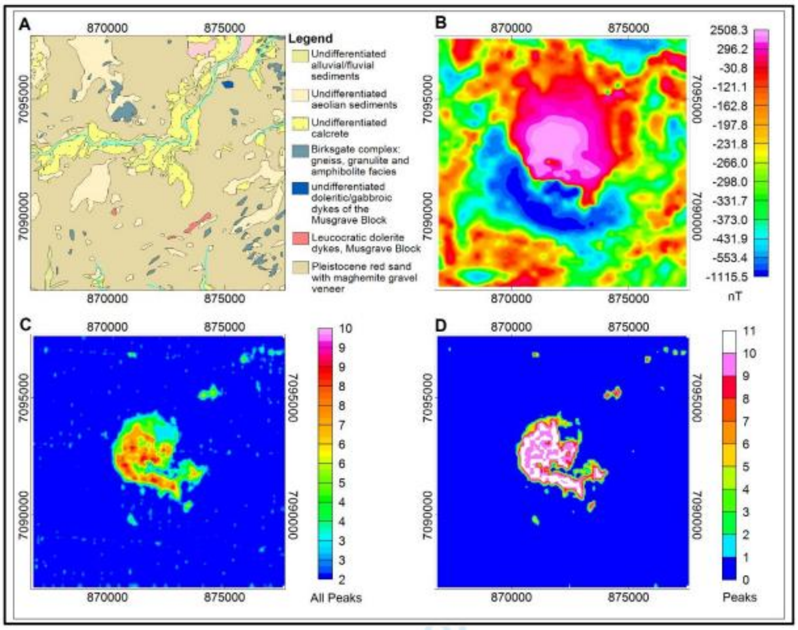

Figure 1. A – Geological map of the study area. B – Total magnetic intensity (TMI) field of Pukatja anomaly, Australia, C – sum of all peaks and D – selected peaks.

Acknowledgement
The authors would like to thank Clive Foss and Juerg Hauser for all their contributions to this work.

Space borne radar imagery in groundwater science

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Space borne radar (SAR) imagery can be used for numerous applications in groundwater science: delimit sedimentary units and fault systems, map land cover and spatial patterns of aquifer recharge, or to monitor ground level and its relation to aquifer hydraulic pressure, compressibility, and thickness. Until recently, these techniques were challenging to apply in Australia due to either the lack of radar imagery archives or to the difficulties in obtaining the archives when available. Since 2015, Sentinel-1 satellites are automatically acquiring images over Earth's landmass and (with constant acquisition geometry) at a 12-days frequency, unleashing an important potential for applications in Australia. In this presentation, I explain the principles of acquisition and processing of radar imagery and provide an overview of applications in Australia. I also illustrate the challenges that hydrogeologists might face while integrating this data into their work.

Radar Interferometry (InSAR) allows to derive ground level changes from radar image time-series. Over Perth basin and Murrumbidgee regions, trends in ground level changes (subsidence or uplift) are obtained from InSAR and show that significant groundwater storage changes have occurred during 2016-2019. In other areas, the interpretation of InSAR results is challenged by the important clay content in the surficial layers of soils, which induces large seasonal changes in ground level not attributable to groundwater storage. SAR imagery is also used to monitor the structural stability of vegetation during droughts, which is used to infer its reliance on groundwater [1]. Finally, SAR imagery can be combined with time-variable gravity measurements for high-resolution, volumetric mapping of groundwater depletion [2]. While such research has been carried in Central Mexico, several contributors to the gravity signal need to be removed before applying it in Australia [3].

Acknowledgement
The author acknowledges Luk Peeters (CSIRO, DEI FSP), Feng Wei (Chinese Academy of Sciences) and Laurent Longuevergne (CNRS, France).

References

[1] Castellazzi, P., Doody, T., Peeters, L., 2019. Toward monitoring groundwater-dependant ecosystems using SAR imagery. Hydrol. Process. https://doi.org/10.1002/hyp.13570
[2] Castellazzi, P., Longuevergne, L., Martel, R., Rivera, A., Brouard, C., Chaussard, E., 2018. Quantitative mapping of groundwater depletion at the water management scale using a combined GRACE/InSAR approach. Remote Sens. Environ. 205. https://doi.org/10.1016/j.rse.2017.11.025
[3] Castellazzi, P., Under Review. 'Mining exports and climate variability influencing GRACE-derived water storage trend estimates in Australia'. IGARSS 2020 Conference Proceeding.

Empirical Green's function retrieval using ambient noise source-receiver interferometry

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Empirical Green's function (EGF) retrieval commonly relies on cross-correlating the long-term ambient seismic wavefield that is simultaneously recorded at multiple stations. Recent studies have demonstrated observationally that cross-correlating the coda of ambient noise cross-correlation functions enables reconstruction of the EGFs, regardless of the operating time of the stations. In this study, we examine the feasibility of using the non-diffuse energy (i.e., surface waves) of the ambient cross-correlation functions to retrieve EGFs between asynchronous stations. We show that source-receiver interferometry (SRI), which is conventionally applied to reconstruct virtual seismograms between earthquake-station pairs, provides an effective framework to retrieve EGFs between asynchronous stations. SRI exploits the non-diffuse wavefield rather than the scattered coda waves that may be contaminated by incoherent energy under non-ideal (e.g., sparse, noisy and short-duration) network configurations. We first demonstrate the robustness of SRI by retrieving asynchronous EGFs and performing seismic tomography between 1) nearby stations and 2) distant temporary arrays from southern Australia. The additional ray paths from asynchronous EGFs provide better illumination of small-scale crustal structures beneath the regional network. In the larger-scale example, involving two asynchronous arrays, SRI offers new constraints to the sparsely sampled region along the continental margin of southern Australia.

We then apply the proposed workflow to seismic imaging of the Australian continent. Our dataset consists of continuous seismic recordings from over 1400 stations deployed between 1994-2019. Among them, over 200 long operating stations are employed as virtual sources by SRI to tie temporary deployments with asynchronous operating periods. This provides over half million new cross-correlation functions in addition to those from synchronous stations using conventional ambient noise correlation. The group velocities between 5-35 sec are inverted from 12,0000 high-quality cross-correlation functions, including 90000 measurements from the asynchronous station pairs, which provide the most detailed continental-scale seismic model of Australia to date. Our model is highlighted by 1) highly consistent spatial distribution of low velocities and known sedimentary basins and 2) the illumination of small-scale basins (e.g., Perth basin) near the continental margins. This study demonstrates that SRI is a promising tool for integrating transportable arrays operated at different times and can greatly benefit the effort of improving data coverage and resolution in seismic imaging.

Controls on the stratigraphic evolution of the Velkerri and Kyalla formations of the Beetaloo Basin (N.T., Australia)

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Shale plays' prospectivity and producibility are closely related to organic content, thermal maturity, porosity, permeability and brittleness of the reservoir intervals. All these parameters are themselves controlled by sedimentary facies, mineralogy and thermal history. Therefore, being able to conceptualise the geological controls on the stratigraphic architecture and resulting sedimentary facies distribution is paramount to properly asses the quantity of recoverable hydrocarbons in unconventional reservoirs.

The Northern Territory of Australia and its Beetaloo Basin presents a colossal potential for these unconventional hydrocarbons with primary targets located in the Mesoproterozoic Velkerri and Kyalla formations. In this basin, the challenges of unconventional resource exploration are exacerbated by age of the shales (ca. 1.4 Ga), complex geological history and the paucity of data to accurately map key elements of the petroleum system. The aim of this study is to improve our understanding of controls on the sedimentary heterogeneity (e.g. organic richness, mineralogy) in these Mesoproterozoic formations using stratigraphy and geochemistry.

Based on well data distributed along two basin-scale sections (N-S and E-W), we reconstruct the stratigraphic architecture of the Velkerri and Kyalla formations. We discuss regional controls, such as sediment provenance and paleogeography on the architecture. Lastly, by integrating geochemical data in the stratigraphic architecture we discuss the distribution of organic-rich intervals in the stratigraphic framework and its potential controls.

Understanding sedimentary basin's gravity response variability using stratigraphic parameterisation

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It is accepted that gravity inversions are non-unique and that multiple models will fit the data equally well. This non-uniqueness extends beyond the choice of parameter values to the choice of model parameterisation: a voxel-based model is likely to explain the data as well as a layer-based model with constant density and variable thickness. A practical first-order consequence of this non-uniqueness is the fact that the measured gravity response above a sedimentary basin can be related to (1) sediments with constant densities above a highly heterogeneous basement or to (2) a basement with a constant density combined with variations of densities within the sedimentary strata. Understanding the sedimentary cover's gravity response and its variability is therefore paramount to generate hypotheses on the causal mechanisms of observed gravity response anomalies.

We explore stratigraphic modelling as a new parameterisation for gravity models to assess the variability of sedimentary strata's gravity response. Using a process-based numerical simulation to generate the density models used in forward gravity modelling we seek to focus only on geologically plausible models. Results from a study of a 2D section in the Northern Carnarvon basin (northwest shelf of Australia) show that even with a wide range of input parameters for the stratigraphic models, the modelled gravity response still has a limited variability when compared to model results generated using subsurface density distribution parameterised with voxels or layers. Further to this, our results provide insight into the global sensitivity of the gravity response to geologic and stratigraphic controls.

Seismic signature of gold mineralization from laboratory rock physics and petrology characterization

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Gold deposits are becoming deeper or are still concealed under a deeply weathered terrain. Therefore, exploratory and mining planning activities require detailed structural imaging to reduce associated drilling costs. Among imaging techniques, seismic methods are an appealing geophysical tool to consider and adapt for mineral settings as they indeed simultaneously join resolution and depth of investigation.

Direct detection of gold is difficult because the ore is in low concentration in the rock. However, gold deposits are commonly associated with characteristic alteration zones when related to particular host rocks. Identifying this indirect indicator of gold mineralization could be used for targeted drilling.

To better understand the elastic properties and their changes with alteration in gold deposits environments, we characterized in the laboratory more than 100 core samples from 2 mines sites in Western Australia: Karari and Thunderbox mines. Rock Physics laboratory measurements include bulk and grain densities, porosities, and ultrasonic P- and S-wave velocities, in the axial and radial directions of the cores. Mineralogical characterizations, conducted on a subset of representative samples of different alteration zones and lithologies, comprise XRD analyses for mineral identification and automated mineral mapping. These experimental data were used as input in different rock physics models to find one that is consistent with our data. The overall goal is to understand the effects of mineralogy and texture on the elastic properties of the samples.

The first results indicate that the texture of the host rocks, namely foliation and porosity (even 2%), is the primary control of the elastic properties variation. These results will help to predict the seismic properties of typical alteration zones associated with lode gold deposits, and to infer whether textural changes, mineralogical changes or larger scale structural features will give a response in the seismic signal.

Acknowledgement

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Exploring links between resistivity and thermal maturity in organic-rich shales

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The petrophysical signature of organic-rich shale is determined by their mineral and organic matter assemblage and the nature and distribution of fluids. Electrical resistivity has been widely used as an effective proxy for detection of organic matter and hydrocarbons in shales. Up to thermal maturities within the oil window, the so-called delta log R method (Passey et al., 1990) is used to estimate organic richness of potential source rocks from the sonic and the resistivity wireline log curves. However, at higher thermal maturities, the sediments undergo chemical and structural reorganization involving loss of hydrogen and oxygen and aromatization of the organic component leading to a dramatic decrease in its electrical resistivity. This influence, especially at thermal maturities consistent with and beyond the gas generation window is not accounted for in petrophysical log interpretation and the petrophysical properties of over-mature shales are poorly documented in the literature.

We show examples of hydrocarbon prospective shales characterized by low electrical resistivity of the organic-rich sections and through an integrated petrophysical, petrological, and nanoanalytical approach we show that the anomalous conductivity is related to a conductive, connected network of partially graphitised bitumen and not to commonly assumed accessory conductive minerals such as pyrite. This interpretation is verified by several case studies on prospective organic-rich shales that have been exposed to high thermal maturation induced by either deep burial conditions (Appalachian Basin, USA; Sichuan Basin, China), or contact metamorphism (Beetaloo Basin, Australia).

Importantly, these results can help better define prospective areas of hydrocarbon accumulation in sedimentary basins as well as potentially identify false positives in the geophysical signature of mineralization under cover.

Acknowledgements
Part of this study was conducted under the SHARC2 joint industry project sponsored by BG Group, Sinopec, Saudi Aramco, and BP. We thank Ben Clennell and Matthew Josh (CSIRO Energy) for valuable discussions on the petrophysical properties of shales and William Rickard (Curtin University) and Martin Saunders (University of Western Australia) for their help with electron microscopy and sample preparation.

References
Passey, Q. R., S. Creaney, J. B. Kulla, F. J. Moretti, and J. D. Stroud, 1990, A practical model for organic richness from porosity and resistivity logs: AAPG Bulletin, 74, no. 12, 1777–1794.

Bayesian trans-dimensional reflection full waveform inversion: synthetic and field data application

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Seismic full waveform inversion (FWI) is a state-of-the-art technique for estimating subsurface physical models from recorded seismic waveform, but its application requires care because of high non-linearity and non-uniqueness. The conventional FWI is an linearised process, with local gradient information to iteratively update the model; the global convergence relies on an informative starting model. Bayesian inference using Markov chain Monte Carlo (MCMC) sampling is able to remove such dependence, by an extensive direct search of the model space. We use a Bayesian trans-dimensional MCMC seismic FWI method with a parsimonious dipping layer parameterization [2], to invert for subsurface velocity models from prestack seismic common-source gathers. For the synthetic study, we use a simple four-layer model and a modified Marmousi model. A recently collected multi-channel offshore seismic reflection dataset, from the Lord Howe Rise (LHR) in the east of Australia, is used for the field data test.

The trans-dimensional FWI method is able to provide model ensembles for describing the posterior distribution, when the dipping-layer model assumption satisfies the observed data. The model assumption requires narrow models, thus only near-offset data to be used. We use model stitching with lateral and depth constraints to create larger 2D models from many adjacent overlapping sub-model inversions.

The inverted 2D velocity model from the Bayesian inference is then used as a starting model for the gradient-based FWI, from which we are able to obtain high-resolution subsurface velocity models, as demonstrated using the synthetic data. However, lacking far-offset data limits the constraints for the low-wavenumber part of the velocity model, making the inversion highly non-unique. We found it challenging to apply the dipping-layer based Bayesian FWI to the field data. The approximations in the source wavelet and forward modeling physics increase the multi-modality of the posterior distribution; the sampled velocity models clearly show the tradeoff between interface depth and velocity. Numerical examples using the synthetic and field data indicate that trans-dimensional FWI has the potential for inverting earth models from reflection waveform. However, a sparse model parameterization and far offset constraints are required, especially for field application.

Acknowledgement
The authors thank Geoscience Australia for providing the field seismic data from the Lord Howe Rise. This work was supported by resources provided by the Pawsey Supercomputing Centre with funding from the Deep Earth Imaging Future Science Platform, CSIRO, the Australian Government and the Government of Western Australia.

References
[1] Visser, G., Guo, P., & Saygin, E., 2019. Bayesian transdimensional seismic full waveform inversion with a dipping layer parameterization, *Geophysics*, 84(6), 1–60.

GIS based fault and fracture network analysis

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Fault and fracture networks channel or impede fluid flow in the subsurface. They become major drivers of the flow dynamic in low-porosity rocks, in which their geometry and topology govern the flow pattern on a regional scale. The objective of this study is to design an efficient and robust method to characterise geometry and topology of discontinuity networks that are represented by vector data. Linking raster data (i.e. elevation, magnetic or gravity data) to the network components allows for further characterization of the lineaments and preliminary assessment of dominant fluid pathways.

We present an automated framework for data extraction and analysis, based on graph representations of 2D fault and fracture networks. Initially, the consistence of the vector data is tested and flaws such as segmented discontinuity traces are automatically corrected. In the subsequent steps of the analysis the geometric parameters are extracted, and their distributions are determined. In addition to the geometric analysis we investigate the spatial arrangement and network topology. The spatial arrangement is analysed in terms of density and fractal dimension. In order to characterise the connectivity a georeferenced graph is produced. This data structure can also be linked to raster data for further lineaments characterisation. In addition, we show how standard graph algorithms (such as shortest path and maximum flow) allow for assessing fluid flow. Following the generation of the descriptive statistics, a 2D finite element mesh is generated from the vector data. This allows for more detailed studies on fluid flow in the networks and evaluation of the predictions obtained through graph analysis.

In summary, our analytical framework allows for characterising geometric and topological properties of lineament networks, determines potential sub-networks, and applies standard graph algorithms to obtain additional information on the fluid flow properties. We compare the predictions obtained from the graph analysis with fluid flow simulations performed on the generated meshes.

Velocity model building and arrival classification using expectation-maximization

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Inversion of seismic traveltime data for velocity model inference is a technique commonly employed across a broad range of subsurface imaging applications (e.g. crustal transects, earthquake location, vertical seismic profiling). In all applications, model inference given the seismic traveltime data is reliant on the ability to appropriately identify ray theoretical arrivals and assign a travel time. Generating these traveltime datasets can be a time consuming and often iterative task, requiring (1) identification and (2) picking of arrivals as well as (3) classification of the arrival type or phase. Moreover, arrival identification, picking, and classification is typically carried out independently of inversion of the traveltime data. This sequential approach can be potentially detrimental, as it is well understood that uncertainties associated with the identification of individual arrivals and the determination of traveltime contribute to overall model uncertainty. As a source of uncertainty, the arrival classification is often overlooked or ignored in these sequential approaches and potential misclassification of arrivals can lead to erroneous velocity models.

To appropriately address and handle these aspects of uncertainty within a unified framework, we propose an approach that treats arrival classification and velocity model building as a joint problem using the expectation-maximization (EM) algorithm (Dempster et al., 1977). We introduce the use of an autopicker (Saragiotis et al., 2013) to identify potential arrivals and, via the EM algorithm, select ray theoretical ones for use in the traveltime inversion. In the expectation step the likely class of arrival is estimated and in the subsequent maximization step the velocity model is updated. We demonstrate the feasibility of the method through a synthetic example which yields promising results that show arrival classification can be successfully treated as a free parameter within inversion. We conclude by illustrating and discussing the potential applicability of the method to active source shot gathers.

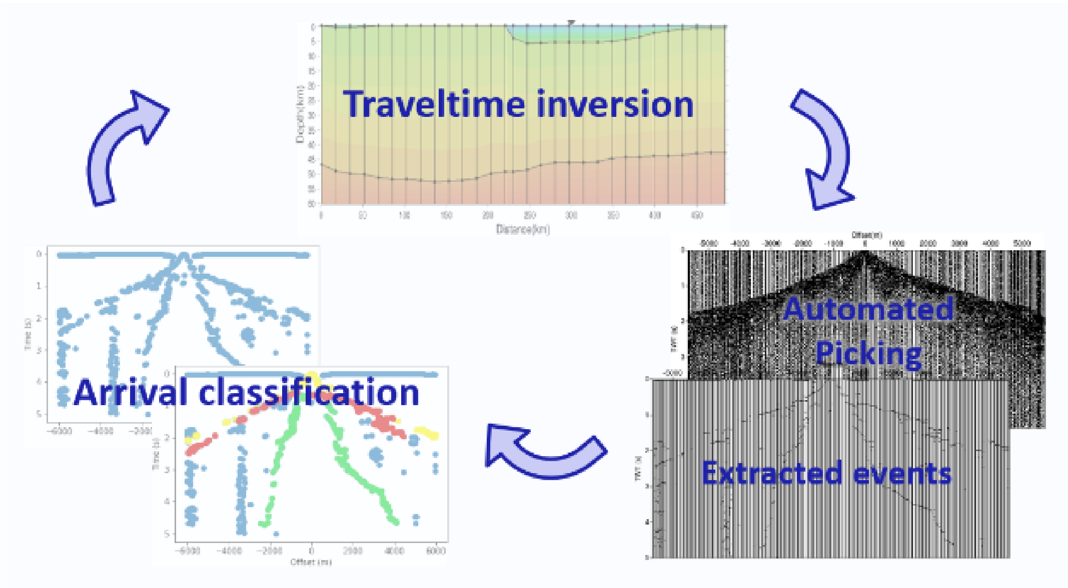

Figure 1. Joint approach to arrival classification and velocity model building

References
Dempster, A. P., N. M. Laird, and D. B. Rubin, 1977, Maximum likelihood from incomplete data via the EM algorithm, 39.
Saragiotis, C., Alkhalifah, T., Fomel, S., 2013, Automatic traveltime picking using instantaneous traveltime. Geophysics, 78(2), T53–T58.

Deep learning for coal seam gas reservoirs exploration

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Deep Learning (DL) approaches have the unique ability to automatically extract features and perform robust predictions and classifications on, large, high-dimensional datasets. The DL approach is valuable for geological problems, where most datasets exhibit non-linear relationships obtained from multiple sources and consist of many heterogeneous observations.

The Autoencoder Neural Networks (AE NNs) is an unsupervised DL method, developed for dimensionality reduction and to facilitate efficient learning from big datasets. AE NNs outperform traditional approaches, such as, Principal Component Analysis (PCA), because of their inherent non-linear transformation ability. Furthermore, their good generalization performance and ability to create an accurate reduced representation of datasets makes them an attractive tool for interrogating geological and geophysical problems.

Ultra-deep coal seams of the Cooper Basin, Australia, have been chosen for this case study because of their potential prospectivity. However, detecting commercially prospective reservoirs is challenging because of the complexities in reservoir and geomechanical properties associated with ultra-deep coals. In this study, we use a dataset of 30 physical parameters estimated from wireline and mudlog wells data for each target coal seams (approximately 1000) located in the Cooper Basin. A two-stage workflow is proposed for the identification of deep coal seam types from well log data: 1) AE NNs is used for extracting features and reducing dimensions of input dataset; 2) Clustering techniques are then used to determine natural groupings of depth intervals associated with various coal seams. The AE NNs revealed dependencies between parameters more efficiently and accurately compared to PCA. Furthermore, the AE NNs-based clustering showed improved spatial separation of clusters along with significant distinct thermal maturity trends in different coal types.

The workflow enables domain experts to explore the hidden non-linear processes and relationships of coal seams parameters, as well as automatically identify various coal seam types from well logs.

Acknowledgement
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References

Dunlop, E. C., Warner, D. S., Warner, P. E. R., and Coleshill, L. R, 2017, Ultra-deep Permian coal gas reservoirs of the Cooper Basin - insights from new studies: The APPEA Journal, 57, 218-262.
Guo, X., Liu, X., Zhu, E., and Yin, J, 2017, Deep Clustering with Convolutional auto-encoders: In 24th International conference on Neural Information Processing, 373-382.

From geological data and historical scenarios to conceptual models

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Regardless of the purposes they deserve or how they are built, geological models often rely on a single geological interpretation. However, were we to ask for a geological interpretation from a hundred different geologists, we would get a hundred different geological interpretations. To minimize the risk of biased and over-confident predictions, modellers need to consider an ensemble of plausible geological interpretations or conceptual models.

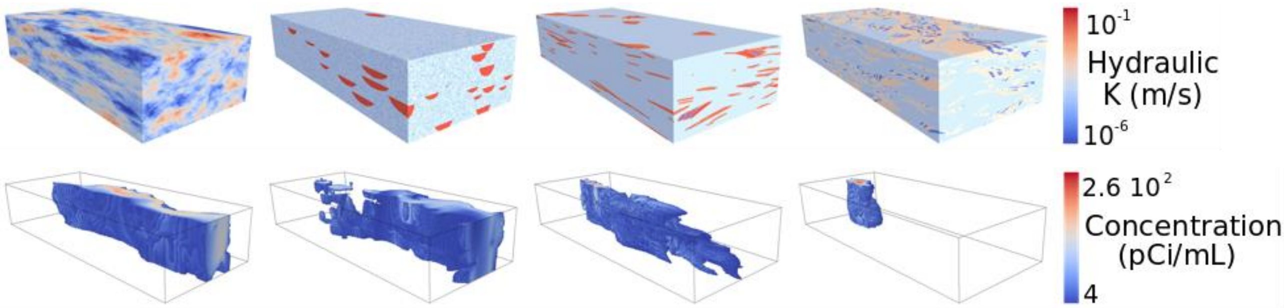

Figure 1. Influence of different geological conceptual models for aquifers (top row) on contaminated plume predictions (bottom row); the mean and variance of the log hydraulic conductivity are constant, but the geometries radically different (courtesy from [1]).

Here, we consider geological data from the Yalgoo-Singleton area and various geological history scenarios to define several plausible conceptual models. The historical scenarios are defined as the product of expert knowledge and combinatorial exploration of geological events. The resulting conceptual models are compared in terms of topology, connectivity and geostatistics.

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References

Pirot, G., P. Renard, E. Huber, J. Straubhaar, and P. Huggenberger, 2015, Influence of conceptual model uncertainty on contaminant transport forecasting in braided river aquifers: Journal of hydrology, 531, 124-141.

Crustal properties from joint inversion of scattered teleseismic body waveforms

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P-to-S receiver functions are a class of converted P to S-waves at seismic discontinuities of the subsurface. They are primarily sensitive to the shear-wave velocity (S-wave) at seismic discontinuities as the reflected, and transmitted P-waves are cancelled by the deconvolution process during the calculation of the P-to-S receiver functions. Autocorrelations of radial and vertical components of teleseismic P-wave coda, on the other hand, include both S- and P-wave reflection responses as well as phases associated with P-to-S-wave conversions below a seismic receiver. Therefore, joint inversion of autocorrelations of vertical and radial components alone or with receiver functions offers a framework which has a great potential to provide more robust estimates of the medium properties at crustal-scale, thus reducing uncertainties surrounding the crustal seismic properties (Vp, Vs and Vp/Vs). There have been many studies about the inversion of receiver functions, but the joint inversion of both radial and vertical components autocorrelations (or with receiver functions) is rare. In this study, we develop a probabilistic joint inversion approach to better constrain both the receiver-side Vp and Vs structures simultaneously, and consequently Vp/Vs crustal structure, which is commonly used to make inferences about the composition of the rocks. We first show the feasibility of using this approach by comparing to single-inversions through a series of synthetic inversion tests. The synthetic tests show that probabilistic joint inversion of autocorrelations of both radial and vertical components provides a robust estimate of the crustal properties and the inclusion of the receiver function into this framework does not provide a better constraint. We then apply the approach on real field passive seismic data, recorded on a series of broadband seismic sensors deployed across a north-south profile in central Australia.

Exploring how rivers and their deposits distort estimates of aquifer recharge using numerical simulations

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Deposits from meandering rivers contribute to the heterogeneity of the subsurface by channeling or diverting groundwater flow. We propose to analyze how the evolution of a river affects this relationship and distort estimates of recharge rates in aquifers. We use the fluvial and stratigraphic modules of the Channel-Hillslope Integrated Landscape Development Model (CHILD) [1] to simulate the evolution and deposits of a meandering river using simplified physical models and rules. Then, we use the fractional packing model [2] to compute porosity and permeability from the resulting unconsolidated sediments. Finally, we use PFLOTRAN [3] to simulate subsurface flow and groundwater age based on a homogeneous recharge from the top. Groundwater age is a key concept to estimate recharge rates using analytical models. Varying aggradation and incision rates of the river lead to a heterogeneous channel belt with varying distributions of coarse deposits. If the channel belt itself funnels the flow, its heterogeneities lead to heterogeneous groundwater ages, even at short distances. This results in varying estimates of recharge rate over the domain (figure 1) and a significant bias even when sampling the subsurface with many wells.

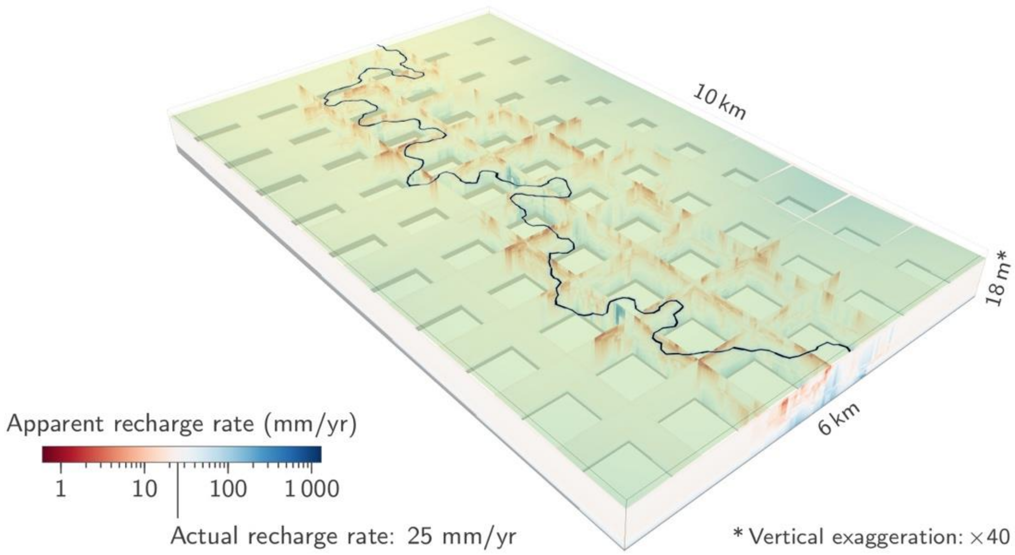

Figure 1. Estimation of the recharge rate in a synthetic aquifer made of fluvial deposits.

References
Clevis, Q., G. E. Tucker, S. T. Lancaster, A. Desitter, N. Gasparini, and G. Lock, 2006, A simple algorithm for the mapping of TIN data onto a static grid: Applied to the stratigraphic simulation of river meander deposits: Computers & Geosciences, 32(6), 749-766.
Koltermann, C. E., and S. M. Gorelick, 1995, Fractional packing model for hydraulic conductivity derived from sediment mixtures: Water Resources Research, 31(12), 3283-3297.
Hammond, G. E., P. C. Lichtner, C. Lu, and R. T. Mills, 2011, PFLOTRAN: Reactive Flow & Transport Code for Use on Laptops to Leadership-Class Supercomputers, in F. Zhang, G. T. G. Yeh, and J. C. Parker, eds., Ground Water Reactive Transport Models: Bentham Science Publishers, 141-159

Surrogate modelling in geophysical inverse problems

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Inverse problems in geophysics are commonly characterized by unfavourable properties such as non-existence of an exact solution, existence of multiple solutions ("non-uniqueness") or instabilities regarding small variations in the observables. Methods such as Markov chain Monte Carlo (McMC) are able to overcome these challenges, but have the drawback of being computationally expensive and even infeasible for some classes of inverse problems. We explore two approaches that aim to mitigate the negative characteristics of McMC: a) exchanging the original forward operator by one that is more efficient, but still sufficiently accurate that could be used within McMC; b) using machine learning concepts to devise new sampling strategies of the model space as an alternative to McMC.

The first approach leads to the creation of surrogate models, which have been successfully applied in engineering and some parts of Earth sciences. This can be achieved by training a neural network to generalize the characteristics of given model-data pairs, leading to a kind of interpolation task. Another idea is to incorporate the physics of the forward operator into a neural network by directly learning the underlying differential equations.

The second approach makes use of a machine learning technique known as generative adversarial networks (GANs). They consist of two neural networks which are trained in a competitive way and have proved to be powerful tools, especially in image processing. Their strength lies in the ability to produce new samples from a given distribution, without explicit knowledge of its mathematical characteristics. GANs promise to provide new ways of efficiently sampling the model space to infer the full solution of an inverse problem by reproducing the data distribution and connect it to the model space by the forward operator or its surrogate.

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Magnetotelluric inversions using structural constrains derived from a probabilistic workflow

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Understanding the architecture of mineral systems from deep sources to shallow mineral deposits has become of great interest for the Australian geoscience community. The structures controlling the formation of a mineral system are generally associated with the presence of fluids migrating from deep sources towards the surface. These structures present strong electrical signatures which can be detected using magnetotelluric (MT) geophysics. Even when dense AMT/MT surveys are carried out the precise and reliable detection of the conductivity anomalies related to mineral deposits are limited by the presence of a thick conductive cover. In these situations, deterministic MT inversion requires significant constraints and regularisation to overcome high non-uniqueness.

We propose an MT data-driven workflow for deriving structural constraints, to enhance the resolution of the conductivity models obtained. We first perform probabilistic inversions using 1D trans-dimensional Markov chain Monte Carlo samplers for estimating subsurface conductivity and its associated uncertainty for each site along a 2D line. These inversions are designed to be robust to non-1D effects present in the data. Next, using a lateral prior and prior petrophysical knowledge, the 1D probabilistic models are fused to form a low resolution 2D posterior ensemble. This is used to derive structural constraints on identified interface locations and layer resistivities. Finally, model roughness penalties are formulated to constrain the 2D deterministic inversion.

This workflow is assessed using synthetic data computed from a realistic 3D Earth. It is then applied on a real dataset to confirm the applicability of the workflow to image complex geological structures and to deal with field MT data. Synthetic and field data results are compared to unconstrained 2D and/or 3D inversions to quantify the improvement in reliability and resolution.

Epigenetic conceptual geochemical modelling of the Century deposit, Mount Isa

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Knowledge of ore-forming processes, identification of mineralogical and geochemical proxies, and discrimination between barren and mineralised units are crucial steps towards the exploration of new orebodies. Reactive transport modelling is useful to predict mineral alteration assemblages, test hypotheses of ore-forming processes, and potentially develop mineralogical and geochemical proxies. The formation of clastic-dominated systems and mineralogical and geochemical proxies is largely based on ore-deposit characterisation. The scope of our study is to use thermodynamic equilibrium modelling to predict mineral assemblages associated with metasomatism in order to strengthen the understanding of sediment-hosted Pb-Zn mineral system formation and their exploration.

We focus on the Century deposit in Mount Isa, where the base-metals are believed to derive from underlying basalts (Peters Creek Volcanics) and the sulfur from an evaporite-bearing sequence (Lady Loretta Formation). Transport occurred via the Termite Range Fault and base-metal deposition in a shale-siltstone sequence of the Lawn Hill formation.

Our approach consists of undertaking 1D reactive transport models that predict the composition of the metalliferous brine which is then used for modelling the deposition of base-metals in the host-rock. Preliminary results for the generation of metalliferous brine show that interaction of one litre of highly saline brine (~20-25 wt% salinity) at a temperature of ~200°C with 10 kg of basalt and anhydrite will result in oxidised fluids (fO_2 =-41) with pH 5.6 that can carry around 16 ppm of Zn. However, the interaction of these fluids with organic-rich shales yield brines with fO_2 of-44 and pH of 5.2 which does not support sphalerite precipitation. Additional models are under development focussing on evaluating the impact of S and C contents in the evaporite and basalt respectively. We also suggest that further dissolution of Zn from the basalt is required and this must occur under more oxidised conditions.

Compressive sensing, compressive inversion? Investigating the potential of sparsity-promoting schemes for geophysical inverse problems

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The concept of compressive sensing has promised a revolution in data collection. Rather than the traditional sampling of a temporal or spatial signal with uniformly distributed samples, compressive sensing promises an exact recovery of the signal with fewer but randomly chosen samples. Provided that the target signal is 'sparse', i.e. has only a few non-zero Fourier components, it can be recovered with high fidelity using inversion algorithms designed to minimize the L1 norm of the recovered solution. Compressive sensing allows signal recovery beyond the Nyquist limit (which requires the signal sampling rate to be at least twice the highest frequency component), allowing high-frequency information to be recorded using relatively few samples.

We explore the concept of 'compressive inversion', applying the mathematical principles that underpin compressive sensing to inverse problems of the form commonly encountered in geophysics. We performed two experiments; one where the measurements are direct and one more complex where the measurements are indirect. We compare the performance of two different regularization methods - L1 and L2 minimization for data recovery. We show that the data can be exactly recovered with a very small number of randomly chosen samples by using L1 minimization.

We also explore the feasibility of developing compressive sensing concept for tomographic imaging problems. Here, a key question is whether the target structure has a sparse representation in some known basis. We show that it is feasible for some geophysical problems, but not all.

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