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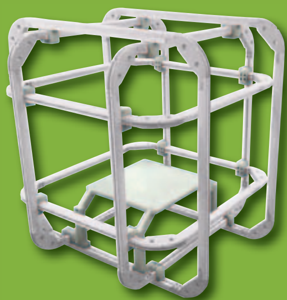
Australian Society of
Exploration Geophysicists

PREVIEW

NEWS AND COMMENTARY

FEATURES



PREVIEW

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2016 ASEG CORPORATE MEMBERS

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The first vehicle borne magnetometer system developed by John Stanley. The development of the system is described by John in his article in this issue of *Preview*.

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Editor's desk

The festive season is upon us and the *Preview* Editorial Team is 'presenting' you with another bumper issue of *Preview*. News and commentary, most particularly news of student projects completed in Australia in 2016, is supplemented by two marvellous features written by two of the 'grand old men' of our profession. Opal, the queen of gems, gets the Don Emerson treatment and John Stanley describes the history of the development of optically pumped magnetometers in Australia – history that is also his story. The recent deaths of Lin Parry and Professor David Boyd (an obituary for Lin Parry appears in this issue and an obituary for David Boyd will appear in the next issue) have made me realise how fortunate we are to have so many older members of our profession staying active and engaging with younger members at ASEG meetings as well as through the pages of *Preview.* I would particularly like to thank Roger Henderson, the Chair of the ASEG History Committee, for facilitating this engagement. Roger is one of the unsung heroes of the ASEG in this regard.

As it is that time of year, I would also like to thank the *Preview* Editorial Team. They do a great job, month after month, of sourcing news and commentary on your behalf. The best present you could give them is your feedback – don't be shy about emailing anyone on the team about anything that takes your fancy! In addition, I would like to thank the *Preview* Production Editor Helen Pavlatos. Helen was on extended sick leave in the period leading up to the publication of this issue of *Preview* and I, for one, was anxiously awaiting news of her recovery.

To complicate matters from the *Preview* perspective, as Helen was returning to work I was jetting halfway round the world to attend a European Union (EU) COST Action meeting in Israel. COST stands for European Cooperation in Science and Technology. This remarkable program was established over 40 years ago to actively support and promote cooperation in science and technology. Funding (over 40 million euros per year) is allocated for networking activities such as meetings (e.g. travel, subsistence and local organiser support), conferences, workshops, short-term scientific exchanges, training schools, publications and dissemination activities. COST does not fund research itself, the focus is on bringing researchers together in order to build trust and to facilitate integration by helping researchers develop a common language – literally and figuratively! English is the *lingua franca* – which is very convenient for those of us who are native English speakers – and ironic as Brexit looms. Fortunately, from my perspective, COST Action groups can and do occasionally invite participants from outside the EU.

The meeting that I attended was a gathering of scientists interested in mapping the movement of water, solutes and sediments across landscapes and within the regolith. Unfortunately none of them were familiar with the very real advances that CRC AMET and CRC LEME had made in this regard. Nor were they familiar with more recent work that had been carried out to improve the processing of EM data. It would seem that although the COST Action program is actively breaking down silos within Europe, there is more work to be done in terms of breaking down barriers that exist between Europe and the rest of the world!

Lisa Worrall
Preview *Editor*
previeweditor@aseg.org.au

The Editor dipping her fingers into the murky waters of the Jordan River. Scientists monitoring the health of this river, which is shrinking and heavily polluted, are handicapped because it is a political boundary. Working from either side they can only carry instruments out to the mid-line before returning to their respective banks.

President's piece

Katherine McKenna

It is yet another sad introduction to my President's Piece with the news of the passing of Professor Boyd. I recently, on behalf of the ASEG, had the pleasure of awarding him the ASEG Gold Medal at the recent ASEG conference. It was during the conference that I had the opportunity to talk to this inspiring individual. I walked away with a new optimism for the world of geophysics and the opportunity it poses for us.

Professor Boyd reminded me that a career in geophysics opens a world of opportunity, and it is the individual who chooses what opportunities to take. During the short period we talked, he also reminded me that there are no barriers other than those that we place in front of ourselves. The enthusiasm and energy that Professor Boyd radiated was intoxicating. Our meeting, which was followed too quickly by the news of his passing, has reminded me that we should be out there getting it done. For this I personally thank him.

Australia is a hub of geophysical knowledge and experience. Our geological environment has forced us to invent, innovate and adapt theories and ideas. Australian geophysical skills have been utilised in many other countries and many have been out there training others as well. Recently I have had a great experience working with the Malaysian Geological Survey. The government is conducting their first airborne geophysical survey in twenty years. The enthusiasm for the project and the possibilities that the results offer for the future of the mineral exploration in the country is an example of the power of geophysics.

The selfie shows many of the Malaysian group inspecting the geophysical aircraft, and demonstrating a huge thirst for knowledge of geophysics. It shows that there are opportunities for Australian geophysicists to promote and transfer our experience and knowledge elsewhere. A famous Roman saying states that by teaching we learn. Nothing can be truer than promoting geophysics through teaching. The e-book from Dave Isles and Leigh Rankin together with the new book from Steve Mudge and Mike Dentith are an example of this transfer of knowledge but there is so much more that can be done.

The second opportunity I had this month was a visit to India. The government there is also undertaking an airborne geophysical survey with the objective of mapping the whole country geologically. The power of geophysics is recognized by the government as playing a part in the economic future of the country. One of the advantages of travelling in the name of geophysics is that you are often watching, or taking part in history. In the case of India I arrived the same day the Prime Minister announced the removal of Rs500 and Rs1000 from circulation, and on the same night of the elections in the United States. It was interesting to watch the first day when the banks reopened the queue of people waiting to try and exchange their money.

Geophysics has certainly offered me the opportunity to travel and see the world, to gain experiences that are more than often unique and to meet the most interesting people that not only share the passion for geophysics but also a passion to learn.

Finally, I would like to wish everyone a safe and merry Christmas. May 2017 bring happiness, security and a renewed enthusiasm for geophysics.

docendo discimus
(by teaching we learn)

Katherine McKenna
ASEG President
president@aseg.org.au

Welcome to new Members

The ASEG extends a warm welcome to 29 new Members approved by the Federal Executive at its October and November meetings (see table).

First name	Last name	Organisation	State	Country	Membership type
Sam	Ballard	Macquarie University	NSW	Australia	Student
Teagan	Blaikie	CSIRO	NT	Australia	Active
Casey	Blundell	Monash University	VIC	Australia	Student
Thomas	Boyle	Curtin University	VIC	Australia	Student
Stephen	Brennan	University of Auckland	Auckland	New Zealand	Student
David	Burt	Vale Exploration Pty Ltd	QLD	Australia	Active
James	Carroll	Bell & Murphy and Associates, LLC	TX	USA	Active
Dennis	Conway	University of Adelaide	SA	Australia	Student
Iain	Copp	University of Western Australia	WA	Australia	Student
Sam	Corbett	FMG	WA	Australia	Active
Charles	Criss	INOVA	CO	USA	Active
Roslyn	Dalton	University of Queensland	QLD	Australia	Student
Stanislav	Glubokovskikh	Curtin University	WA	Australia	Active
Cameron	Graham	University of Queensland	QLD	Australia	Student
Kathryn	Hayward	Australian National University	ACT	Australia	Student
Lachlan	Hennessy	RMIT	VIC	Australia	Student
Sarah	Mason	Curtin University	WA	Australia	Student
Joshua	Meertens	ASST Pty Ltd	WA	Australia	Active
Thomas	Meyer	Lockheed Martin Corp	NY	USA	Active
Michael	Morse	Geoscience Australia	ACT	Australia	Active
Shaun	O'Brien	University of Adelaide	SA	Australia	Student
Mark	Pohutsky	University of Queensland	QLD	Australia	Student
Christian	Richards	AustinBridgeporth	Buckinghamshire	UK	Active
Joseph	Rugari	University of Adelaide	SA	Australia	Student
Todd	Smith	University of Adelaide	SA	Australia	Student
Hernan	Ugalde	Paterson, Grant & Watson Limited	Ontario	Canada	Active
Terry	Visser	Eustatic Resources	WA	Australia	Active
Carmine	Wainman	University of Adelaide	SA	Australia	Student
Nicholas	Wauchope	University of Adelaide	SA	Australia	Student

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Executive brief

The Federal Executive of the ASEG (FedEx) is the governing body of the ASEG. It meets once a month, via teleconference, to see to the administration of the Society. This brief reports on the last monthly meeting, which was held in November. Anyone who would like to see the minutes of the monthly meetings should add their name to the mailing list maintained by the Secretariat. FedEx also holds planning meetings twice a year.

Society finances

The Society's financial position at the end of October:

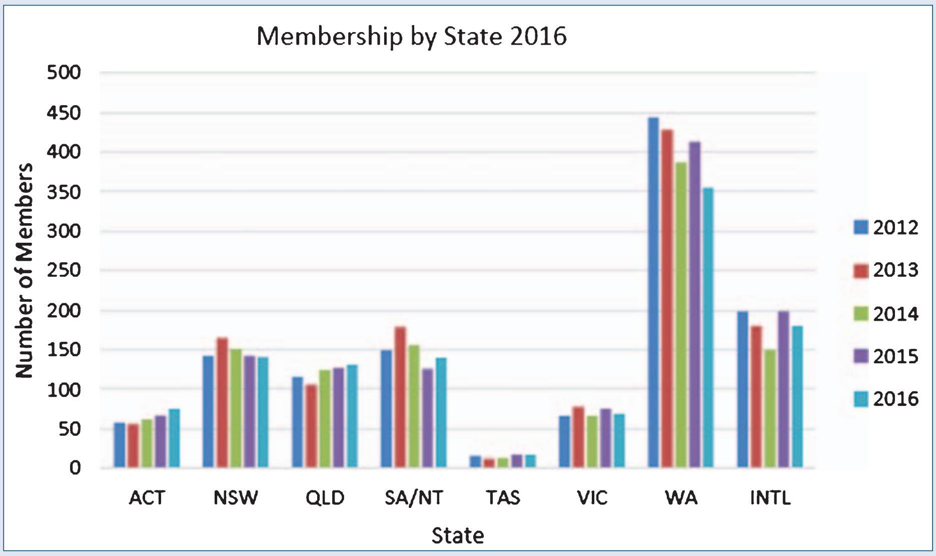
Year to date income $377 716.24
Year to date expenditure $664 807.59
Net assets $1 139 097.66

Membership

As of 30 September 2016, the Society had 1108 Members. Welcome to all of the new Members, particularly the student Members. Remember that early and mid-career Members can join the ASEG Young Professionals Network https://www.aseg.org.au/about-aseg/aseg-young-professionals.

As the holiday season approaches stay safe and visit as many scientific and geological places of interest as you can. From all of us here wishing you all the best at Christmas time and a very Happy New Year.

Marina Costelloe
Honorary Secretary
fedsec@aseg.org.au



ASEG Branch news

Australian Capital Territory

September was kicked off by a visit from **Professor Steven Constable**, a former ANU student, now working at the Scripps Institute of Oceanography. ASEG ACT Members voted for Steven to give a talk on 'Geophysical inversion: which model do you want?'. Stephen illustrated the many ways in which inversion outcomes can be manipulated by factors not associated with the data, such as the error in the data, expected misfits, local and maximum minima misfits among other things. The talk generated a lot of interesting discussion and, in the end, the question time nearly went for as long as the talk itself!

Marina Costelloe, previously the ASEG ACT Branch President and currently a member of the ASEG Federal Executive, presented a talk on her new role with Geoscience Australia titled: 'Geoscience Australia's Geophysical Network; critical infrastructure and observed and derived data for earth modelling and community safety'. The entertaining talk gave an insight into the state-of-the-art network of sophisticated instrumentation that monitors both natural and human-made hazards in Australia. Such was the interest in Marina's talk that a tour of one of the monitoring facilities will be organised for ASEG ACT Members next year.

A distinct advantage of living in Canberra and being a part of the ASEG ACT Branch is having access to talks from notable speakers such as **Dr Brian Kennett**, Emeritus Professor of Seismology at ANU. Brian's talk was on the hot topic that all geophysicists are now interested in, passive seismic. Brian proved his methodology and modelling of 40+ passive stations located over the Fraser Range against gravity modelling and three 2D seismic lines which transect the region. He was also able to model velocity in 3D across the region gaining valuable insight into the 3D structure of the region.

James Goodwin
(ACT Branch Secretary)

New South Wales

In September, the Macquarie University Student Committee did all the hard work. They were given the remit to organise and run the meeting and to attract as many students along as possible. They did an excellent job, with over 40 people attending the meeting, it being the largest held for quite a while.

The abstract for the meeting was:

'Being a student in university is different to life in the geophysics industry. The presenters for this month's Branch meeting have been organised by the ASEG Macquarie University Student Committee. The speakers will be presenting insights into their work and experiences in the industry and how they found the transition from university to industry.'

The speakers were:

Tasman Gillfeather-Clark, Fender Geophysics, Field Technician
Reagan Newton, Roads and Maritime Services, Scientific Officer
Julian Costas, RPS Group Plc, Junior Geophysicist

The students and the 'students at heart' thoroughly enjoyed the evening.

In October, we held our student night and the following students spoke. All talks were well presented and much discussion followed over beers and wine.

Claire Dennerley: Identifying soil sodicity management zones by numerically clustering proximal sensed gamma-ray and EM data at the field scale (UNSW).

Harrison Jones: Geophysical signatures of small-scale base metal occurrences (Macquarie University).

Muddassar Muzzamal: Mapping soil particle-size fractions using additive-log ratio transformation and proximally sensed ancillary data (UNSW).

Bailey Payten: Modelling the evolution of cordillera's at active margins in the context of the Lord Howe Rise (University of Sydney).

Joanna Tobin: Tectonic and geodynamic evolution of the northern Australian margin (University of Sydney).

An invitation to attend NSW Branch meetings is extended to interstate and international visitors who happen to be in town at that time. Meetings are generally held on the third Wednesday of each month from 5:30 pm at the 99 on York Club in the Sydney CBD. Meeting notices, addresses and relevant contact details can be found at the NSW Branch website.

Mark Lackie
(NSW Branch President)

Queensland

The Queensland Branch held its last meeting for the year on Thursday 17 November.

Two students from the University of Queensland presented work they had undertaken in completion of their Honours Theses.

Chris Mathews discussed his work on 'Near-surface characterization from dispersion of Rayleigh and Love waves' while **Shakira Heffner** shared her insights from her work on 'Analysis of azimuthal anisotropy in coal-scale 3D seismic reflection'. Both students did a wonderful job and we welcome them into our professional community.

Chris Mathews and Shakira Heffner.

This month we also recognize our long-serving ASEG Members with Silver certificates distributed to those who have been Members of the ASEG for 25 years. Congratulations and thank you to: **Geoffrey Beckitt**, **John Donohue**, **Karel Driml**, **Sylvia Michael**, **Darcy Milburn**, **Ron Palmer**, **Troy Peters**, **Denis Sweeney**, and **Randall Taylor**.

Our next meeting for the year will be held in February. More details will be

From left to right: Karel Driml, John Donohue, Sylvia Michael, Denis Sweeney and Ron Palmer.

available via the Qld Events tab on the ASEG website in the new year. On behalf of the Queensland Branch I'd like to wish everyone a Merry Christmas and a Happy New Year.

Megan Nightingale
(Qld Branch Secretary)

South Australia & Northern Territory

Since the last edition of *Preview*, the SA/NT Branch has held three events, shifting down a gear as compared to the very busy pace in the months leading up to the ASEG-PESA-AIG 25th International Geophysical Conference and Exhibition. These events included two technical evenings and the ever popular Melbourne Cup Luncheon.

At our September technical evening we were joined by the SEG Distinguished Lecturer **Steven Constable** from the Scripps Institution of Oceanography, La Jolla, California. With a great crowd to present to at the Coopers Alehouse, Steven spoke about some of his recent work, with his talk titled 'Mapping gas hydrate using electromagnetic methods'. It was a brilliant talk giving a very interesting overview of his recent work in gas hydrate mapping and the development and application of electromagnetic receiver technology and the areas in which this EM methodology is being used. Our thanks go to Steven for taking the time to come and present for our branch.

Our annual Industry Night, held at the Coopers Alehouse in September, was the second of the two technical evenings, which gave our valued sponsors the opportunity to showcase the diverse range of projects they are currently involved with. Many thanks go to **Dave Cockshell** from the Department of State Development, **Kate Wittwer** from Minotaur and **Mike Hatch** from Zonge for joining us to present to our membership.

Finally, the annual Melbourne Cup Luncheon was a great success. With the Calcutta Sweep producing some unlikely winners, prizes for the best dress colt and filly and a great atmosphere in the packed venue, much fun was had throughout the day and into the evening. I would like to thank our Branch sponsors, the Ambassadors Hotel for holding this year's event and **Matt Hutchens**, **Adam Davey** and **Phil Heath** and all the Committee Members who lent a hand, without whom the day would not have come together. I would especially like to thank **Neil Gibbins**, who under considerably adverse conditions with the AV, managed to pull the whole day back on track. With very quick, out of the box thinking we were able to watch and importantly hear the race. Who would have thought that would be so important at a Melbourne Cup Luncheon!

All of our technical meetings and events are made possible by our very generous group of sponsors, which in 2016 includes the Department of State Development, Beach Energy, Minotaur Exploration, Borehole Wireline and Zonge. We will be in touch with other previous sponsors hoping they will return again next year. Of course, if you or your company are not in that list and would like to offer your support, please get in touch at the email address below.

By the time you are reading this there will be no more events scheduled for 2016 as we go into the holiday season. Keep an eye out for events in 2017 on the website and in your inbox, further technical meetings will be held monthly at the Coopers Alehouse on Hurtle Square in the early evening, starting in February with the AGM, date TBA. If you are interested in joining the Committee or holding a position on the Branch Executive, nomination forms will be sent out early next year.

We invite all Members, both SA/NT and interstate to attend our events, and of course any new Members or interested persons are also very welcome to join us. For any further information or event details, please check the ASEG website under SA/NT Branch events and please do not hesitate to get in touch at joshua.sage@beachenergy.com.au or on 8338 2833.

Josh Sage
(SA/NT Branch President)

Tasmania

ASEG members played key roles in tectonically themed presentations to the geoscience community in Hobart during October and November. Though both dealt with tectonic reconstructions, they did so from opposite ends of the Australian plate in a spatial and to some extent temporal sense, but both using potential field geophysics to a significant extent.

Marine geophysicist **Joanne Whittaker** of the Institute for Marine and Antarctic Studies outlined the evidence for micro-continents offshore Western Australia and their implications for East Gondwana reconstructions, on October 27. Then on 8 November, recent Monash PhD graduate (he may have previously done one or two other things too) **David Moore** added his model to the melting pot of new ideas surrounding the pre-Ordovician development of western Tasmanian lithosphere leading up to its incorporation as 'VanDieland' within what became Gondwana generally, and southeast Australia in particular. Thanks to the Geological Society of Australia's Tasmania Branch for arranging these talks and extending an invitation for ASEG Members to attend them.

In the new year, look out for **Anton Rada** talking about his newly developed UAV geophysical data acquisition system, details TBA.

An invitation to attend Tasmanian Branch meetings is extended to all ASEG Members and interested parties. Meetings are usually held in the CODES Conference Room, University of Tasmania, Hobart. Meeting notices, details about venues and relevant contact details can be found on the Tasmanian Branch page on the ASEG website. Interested Members and other parties should also keep an eye on the seminar program of the University of Tasmania's School of Earth Sciences, which regularly delivers presentations of geophysical as well as general earth science interest. Contact **Mark Duffett** taspresident@aseg.org.au for further details.

Mark Duffett
(Tasmanian Branch President)

Victoria

On 26 September The Victorian Branch had the pleasure of welcoming our SEG lecturer from the US (University of California, San Diego), **Professor Steven Constable**, who gave a talk entitled 'Geophyscial inversion: which model do you want?'. Steven enlightened us about the many pitfalls which present

ASEG news

themselves when proceeding to geophysical inversion. This was a very well received talk with the best attendance of the year! Thank you Steven and the SEG.

On 15 November the Branch hosted the annual student night, when current students from the University of Melbourne, Monash University and RMIT presented on the state of their research project. RMIT PhD student **Lachlan Hennessy** received the first prize for his work on 'Magneto-tellurics with lightning source information'. The Victorian Branch Student Night is reported on in more detail in the *Education Matters* section of this issue of *Preview*.

Seda Rouxel
(Victorian Branch President)

Western Australia

The WA Branch hosted a presentation from **Lee Steven** of Geosoft on 'Delivering multi-disciplinary geoscience data to industry' on 12 October at the Celtic Club, an alternative venue to City West and currently on trial. Lee drew his discussion from recent work with QDEX, from the Queensland Department of Natural Resources and Mines and the Botswana Geoscience Portal from the Botswana Geological Survey. Managing and distributing large datasets continues to challenge both government and end users so this update was timely and interesting.

The first event for November was the PESA-ASEG Golf Day which was held on Friday 11 November at the Novotel Vines Resort in the Swan Valley. This annual social event attracted 108 golfers. While sponsorship was down for the year, enthusiasm for the game from Members and guests was just as keen.

On 24 November the Branch hosted presentations from five of this year's students. Student awards for 2016 were announced after the talks, which was held in the City West Function Centre.

Our final technical presentation will be hosted at the Celtic Club on 7 December when **Allan Trench** will present current trends with mineral economics. The ASEG Annual General Meeting will precede the talk so all local Members are encouraged to attend. Christmas drinks and a light meal of South East Asian curries, sambals and rice will follow Allan's presentation.

Finally, the WA Branch would like to congratulate our President, **Kathlene Oliver**. Kathlene was awarded the ASEG Service Certificate at the ASEG-PESA-AIG conference for 2016 held in Adelaide at the end of August for her sterling effort at returning the WA Branch to profitability, steering it through a couple of eventful and interesting years, and focusing on enhancing diversity and the feeling of inclusiveness for Members at events.

Kathlene Oliver
(WA Branch President)

ASEG national calendar: technical meetings, courses and events

Date	Branch	Event	Presenter	Time	Venue
2016					
2 Dec	SA-NT	SAEMC (http://www.saexplorers.com.au/)	Various	0800–1700	Adelaide Convention Centre, Adelaide
7 Dec	WA	AGM, Tech night and Christmas party	Allan Trench	1730–2000	Celtic Club, 48 Ord Street, West Perth
14 Dec	NSW	Quiz night	TBA	TBA	99 on York Club, Sydney CBD
14 Dec	Vic	Christmas lunch with PESA and SPE	TBA	TBA	TBA
15 Dec	ACT	Tech talks	Various	TBA	Sir Harold Raggatt Theatre, Geoscience Australia, Symonston, Canberra
2017					
Feb	SA-NT	AGM	TBA	1730	Coopers Alehouse, Hurtle Square, Adelaide
Feb	Qld	AGM	TBA	1730	XXXX Brewery, Corner of Black Street and Paten Street, Milton
8 Feb	WA	Tech night	Dave Annetts	1730–1900	TBA
15 Feb	NSW	AGM	TBA	TBA	99 on York Club, Sydney CBD
9 Mar	WA	Tech night	Shane Evans	1730–1900	TBA

TBA, to be advised (please contact your state Branch Secretary for more information).

Vale Lindsay (Lin) George Parry (1922–2016)

Lindsay George Parry in the early 1950s.

Lin Parry was born at home on a farm near Ballina, on the north coast of NSW, Australia, 29 March 1922, where he spent the first 16 years of his life. There was no bus service to the school in nearby Wardell so he had an extended pre-school with charcoal and the concrete floor of the cow bails substituting for a chalk and blackboard. With his Mother's help Lin soon learned some letters and numbers, thereby completing much of the kindergarten material. Finally, at the age of seven Lin went to school.

Starting late, Lin's primary schooling was disjointed. With continuing transport problems and completing two years by correspondence, Lin nevertheless passed the final primary school examination thereby graduating to high school. The eventual transport solution for high school was a bicycle; ride to Wardell, park the bike, cross the river by ferry, and catch the school bus to Ballina High. Due to his fragmented schooling to this point Lin was enrolled in the B class. Nevertheless, at the end of first year Lin was dux of his year. At the end of high school Lin's Leaving Certificate results were: English A; Maths I & II – Hons II; History A; French B; Chemistry B; Geography B, one of the best results on the North Coast.

Based on Lin's Leaving Certificate results he was awarded a Teachers' College Scholarship at Armidale with the aim of becoming a high school teacher. Part of his studies included university courses for which he was awarded a BSc Dip Ed from Sydney University.

Lin married Margaret in 1947 and their son Graham was born in 1948, followed by their daughter Susan in 1952. After teaching briefly at Bathurst High School Lin was appointed to the University of New South Wales (UNSW) when it was still emerging from its foundation in the Sydney Technical College. Conceived as a specialised training institute for engineers, staff were also recruited to teach ancillary subjects, such as Physics, which is where Parry fitted in. The evolution from its technical college origins to a fully-fledged university introduced new expectations of teaching staff, research and publication in particular. Lin was a founding member of the Physics Department and completed his MSc in 1955, which was presented at the first degree ceremony at UNSW. Lin was to spend his entire professional life at the UNSW.

One of the advantages of university work was sabbatical leave and Lin was able to avail himself of it on three occasions. In 1957 Lin took his family to Canberra where he was able to work on magnetic properties (particularly thermo-magnetic) of various materials and more especially with some of the leaders in the field at ANU. During this first study leave at ANU he was able to work with Frank Stacey. Lin and Margaret and Frank, and his wife Joy, were to become great friends. In his memoirs Lin recalls 'when we were considering the grains of magnetite too small to accommodate a full domain structure but not small enough to be one domain he (Frank) produced the theory in a very short time all written up and ready to publish and only needing some experimental evidence. One of the best scholars and the greatest scientist I knew'. Therefore Lin took the lead in developing a translation balance for measurement of the temperature dependence of the saturation magnetisations of rocks, to identify the compositions of their magnetically active minerals. He subsequently produced a similar instrument in Sydney and this work became central to his research.

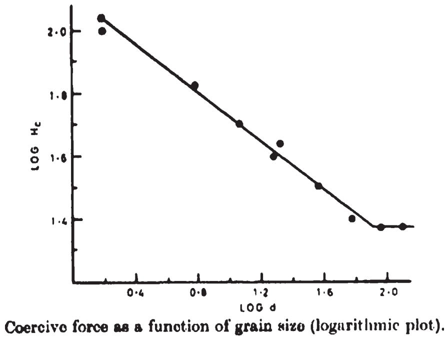


Figure 1. *The power relation between coercivity and grain-size determined by Parry (1965) confirmed Stacey's theory albeit the annealing beforehand yielded magnetically softer titanomagnetites.*

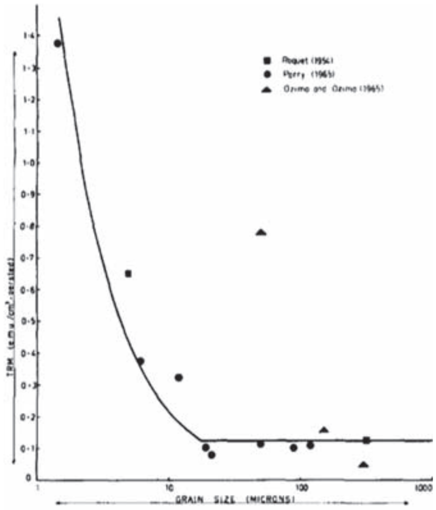


Figure 2. *Dickson et al.'s Fig. 1 combining Roquet's (1954), Parry's (1965) and Ozima and Ozima's (1965) thermoremanent magnetisation (TRM) vs grain-size results showing the abrupt onset of multidomain behaviour above 20 μm where TRM is no longer a function of grain-size or coercivity.*

The translation balance had two interesting applications resulting directly from his ANU contacts. One was with John Lovering, a geochemist with a special interest in meteorites that had magnetic remanences apparently predating their arrival on the Earth. Parry's role was to identify the Fe-Ni alloy phases, evolution of which during cooling controlled the remanences. Another ANU collaborator was Ted Irving, who was establishing the polar wander path for Australia. Irving had found rocks near Kiama, south of Sydney in NSW, which had consistently reversed remanence over a 50 million year age range. We now know of this as the Kiaman reverse superchron, but its plausibility was subject to some doubt at the time. One of the contrary postulates was that there was a subtle but systematic difference between the magnetic constituents of reversed and normally magnetised rocks, allowing the possibility of self-reversing remanence by one of the mechanisms suggested by Louis Néel.

Lin with his post-grad students in 1971. Clockwise beginning left front, A.A. Rahman (MSc PhD), L.G. Little (MSc), M.F. Westcott-Lewis (MSc PhD), A.D. Duncan (MSc) and B.W. Robins (PhD).

Parry's measurements on Irving's rocks showed no such effect.

For the second crucial sabbatical in 1964 in Newcastle, Parry joined what was then the strongest rock magnetism group anywhere, led by Keith Runcorn. By then the phenomenon of thermoremanence had been quite intensively observed but the theory was lagging. A satisfying interpretation of its grain size dependence was still needed and a basic difficulty was that there were no well controlled experiments that made clear just what the dependence was. Parry filled the gap by using an elutriator to separate magnetite grains of different sizes and dispersing them in a non-magnetic matrix to simulate rocks for which he measured all the standard properties, including thermoremanence. The result was a data set that became a standard reference for magnetic properties of dispersed fine grains. It clearly identified the range of grain sizes displaying pseudo-single domain properties, resolving the question of what distinguishes the grains that are responsible for most of the magnetically stable rocks from the single domains of Néel's pioneering theory and true multidomains. During this time Lin wrote, and Margaret typed, his PhD thesis which was awarded by UNSW in 1965.

Lin's third sabbatical in 1972 was with Rod Wilson's group, Liverpool University, where he continued studying the magnetic properties of fine particles using Rod's vast sample collection from young lavas and dykes.

By nature, Lin Parry was a collaborator, disinclined to emphasise what he, himself, was doing. He saw the physical problems that arose in other people's work and applied his experimental skills to resolving them. The names of graduate students he supervised later in his career are distributed through the literature with little indication of his role in inspiring their work. The following list of publications is far from comprehensive but gives an idea of the developments of his research interest through the years, from beach sands and meteorites to common garden rocks, while at the same time focussed very much on the magnetisation of micron to sub-micron titanomagnetite particles. Lin characteristically assumed junior authorship in publications with his students.

Selected list of publications

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Parry, L. G., 1982, Magnetization of immobilized particle dispersions with two distinct particle sizes: *Physics of the Earth and Planetary Interiors*, **28**(3), 230–241.

I should like to acknowledge information and photos provided to me by Lin's son Graham and Frank Stacey. The main photograph was provided to Graham from the UNSW Archives.

Phil Schmidt
phil@magneticearth.com.au

Editor's note: The Institute for Rock Magnetism (IRM) is thanked for permission to republish this obituary, which first appeared in the 2016 IRM Quarterly 26:2.

News

Where are they now?
Sanjay Govindan: ASEG ACT 2014 Student Travel Award and 2015 Student Award winner

It felt so long ago but in reality just a year has passed since I made that frantic dash to my university to submit my final thesis, a milestone that signified the end of my five year commitment to attaining my degree in Engineering and Geology at the Australian National University.

Over the five years there was a plethora of opportunities and choices that contributed to both the success of my undergraduate degree and my ability to transition successfully into the 'real world'. With that being said, no opportunities have been greater than those offered by the Australian Society of Exploration Geophysicists (ASEG). Opportunities such as the Student Travel Award 2014 and the Student Award in 2015 were just added bonuses as the energy and support the ASEG offered through their committed Members was what made all the difference.

The financial support I received from ASEG provided me with the opportunity to present at industry leading conferences such as the Perth ASEG Conference in 2014 and the 2015 SEG Near Surface Conference held in Hawaii. Furthermore, I was able to attend a range of world class seminars that examined the current bounds of applied geophysics. These high-quality opportunities offered by ASEG led me to undertake an internship with Field Emission Incorporated (FEI) and, more specifically, to conduct a thesis investigating microporous phase flow through high resolution computed tomogram analysis.

the energy and support the ASEG offered through their committed Members was what made all the difference

Throughout my time as a Member of the ASEG, I have continually been inspired by the passionate and world leading experts the ASEG attracts as speakers every year. The ability of geophysics to transcend a range of industries and to incorporate a multitude of technologies has always been able to capture my imagination. Curiosity, intrigue and binge research into theory and technology has followed every ASEG session that I attended. My obsession with examining the relationship between problems and solutions, combined with a penchant for questioning the extent to which technologies can be applied, has been fostered by ASEG and has resulted in me being where I am today.

My current role as a technical consultant for Informed Solutions has allowed me to nurture my interest in bridging the technological gap between problems and solutions in a range of industries all over the world. My current role has seen me involved with a range of bespoke geospatial solutions for clients in the public sector such as the UK central government, Australian State governments and private sector organisations such as BHP.

However, in the not too distant future, my ambition is to dust of my boots, return to the field and rekindle my desire to design digital systems for geophysical and geological applications.

Sanjay Govindan
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SAGA 2017
15th Biennial Conference & Exhibition
10–13 September 2017
The Lord Charles | Cape Town

Expanding Frontiers

September 2017 will see the geophysical fraternity descend upon the winelands of Cape Town for the 15th South African Geophysical Association's Biennial Conference & Exhibition. Once more the Conference will be held in one of South Africa's most attractive locales, the small town of Somerset West. The Lord Charles Hotel is a premier conference venue, just half an hour's drive from Cape Town International Airport and the CBD, its atmosphere will most certainly provide a refined and contemporary backdrop to the event.

Somerset West first appeared in the history books in 1672 after a cattle post was established there by Dutch soldiers. Formally founded in 1822 and located on part of the historic farm of Vergelegen, the town was named after English governor of the Cape Colony, Lord Charles Henry Somerset. The historically-rich region is replete with attractions ranging from world-class wine estates to exquisite nature reserves. As home to the greatest non-tropical concentration of higher plant species, the Cape Floristic Region is also the smallest of the six recognised floral kingdoms of the world and is a highly recommended must-see.

Join us for three days of comprehensive and in-depth talks, complemented by discussions and workshops bracketing the main event. Delegates from both private and public sectors of the mining and petroleum industries as well as leading experts in all disciplines of geophysics will attend. The exhibition affords excellent networking opportunities with all manner of related service providers including consultants and contractors. Delegates are once again afforded the opportunity to invest in our future geoscientists via the 'Adopt-a-Student' mentorship programme.

The talks and workshops will feature hot topics and the most up-to-date content of contemporary of geophysics, including borehole geophysics, potential field geophysics, electrical and electromagnetic geophysics, seismology, minerals exploration, oil and gas exploration, geophysical data processing and modelling, integrated geoscience, near-surface geophysics, geophysics in near mine environments, archaeological, agricultural and bio-geophysics, environmental and engineering geophysics, groundwater and contaminant mapping, unmanned aerial vehicles (UAVs) in geoscience and the structure and evolution of the African continent.

The programme is bursting with intellectual and social events along with exciting pre- and post-conference trips, hosted by local experts to guide your appreciation of the splendour of this region. The SAGA 2017 Committee is proud to be hosting 'special sessions', which will include the launch of a newly established geophysical test site over the world-renowned Vredefort meteorite impact site. Detailed geological and geophysical investigations will be presented with contractors showcasing their efforts.

We're excited to host you and your colleagues in the breath-taking Cape Winelands! Abstract submissions are now open – for further information and early bird registration, visit www.sagaconference.co.za.

News

The Geological Survey of Queensland opens a new $5 million drill core storage facility

Queensland's resources exploration industry now has easier access to drill core thanks to a $5 million expansion of the Queensland Government's Exploration Data Centre (EDC) at Zillmere on Brisbane's north side.

New drill core storage facility at Zillmere.

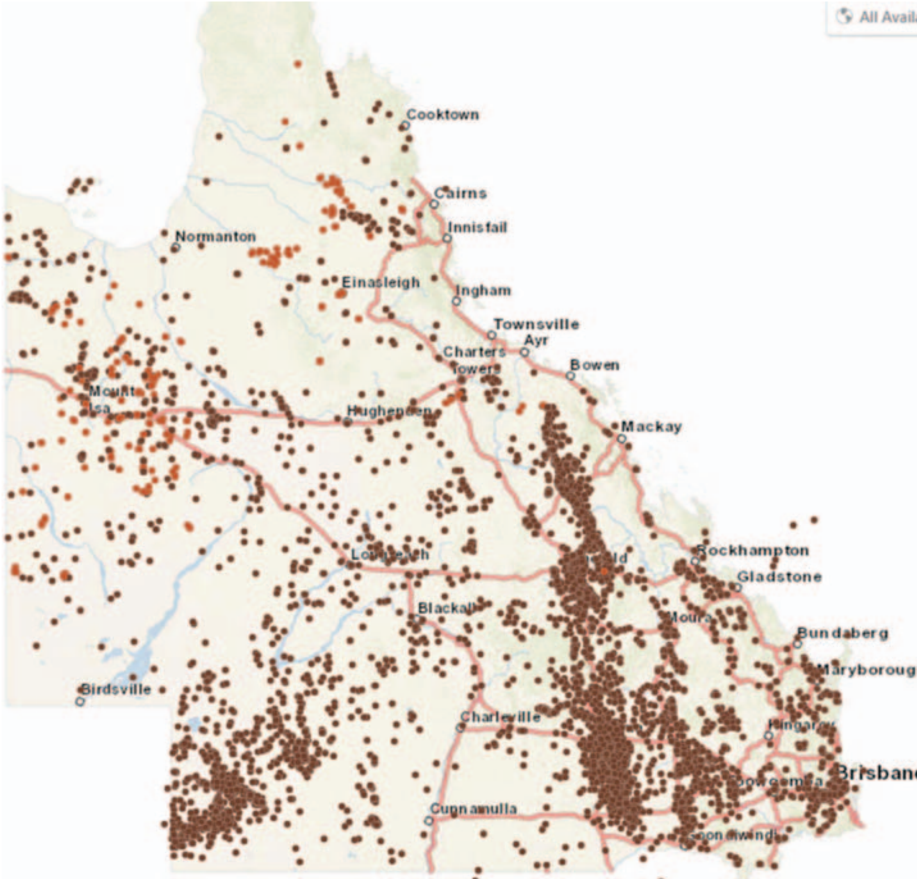

Figure 1. *The collar locations for drill core stored at the new facility.*

The Minister for Natural Resources and Mines, Dr Anthony Lynham, and State Member for Nudgee, Ms Leanne Linard, officially opened the EDC expansion on Thursday 20 October.

The expansion will provide greater access and storage capacity for exploration samples from throughout Queensland, adding to the 800 plus kilometres of core samples currently stored at the facility.

The Exploration Data Centre offers the resources exploration industry a comprehensive catalogue of samples from over 11 600 drill holes collected by the Geological Survey of Queensland over the past 100 years (see Figure 1), with the oldest being from the Mitchell town bore drilled in 1886. The expanded facility will provide storage for an estimated 500 km of additional samples. In addition, the EDC houses the Geological Survey of Queensland's HyLogger™ digital spectral scanning technology.

Queensland's Chief Government Geologist, Tony Knight (left), the Queensland Minister for Natural Resources and Mines, Anthony Lynham, and the State Member for Nudgee, Leanne Linard, at the official opening of the new storage facility.

The centre is open from 8 am to 5 pm Monday to Friday or other times by appointment.

Address and contact details:

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Telephone: +61 7 3096 6810
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Mobile: 0408 887 685
Facebook: Mining Qld
Twitter: @miningqld
https://www.business.qld.gov.au/industry/mining/mining-online-services
https://www.business.qld.gov.au/industry/mining/geoscience-data-information/core-rock-collections

GA: update on geophysical survey progress from the Geological Surveys of Western Australia, South Australia, Northern Territory, Queensland and Victoria (information current on 11 November 2016)

Further information on these surveys is available from Murray Richardson at GA via email at Murray.Richardson@ga.gov.au or telephone on (02) 6249 9229.

Table 1. Airborne magnetic and radiometric surveys

Survey name	Client	Project management	Contractor	Start flying	Line km	Spacing AGL Dir	Area (km²)	End flying	Final data to GA	Locality diagram (*Preview*)	GADDS release
Gawler Craton Oodnadatta	GSSA	GA	TBA	TBA	240 240	200 m	60 m NS or EW	43 680	TBA	183: Aug 2016 p. 34	A contract with the preferred supplier is in the final stages of drafting by GA
Gawler Craton Ooldea	SSA	GA	TBA	TBA	208 560	200 m	60 m NS or EW	37 920	TBA	183: Aug 2016 p. 34	A contract with the preferred supplier is in the final stages of drafting by GA
Gawler Craton Lake Torrens	GSSA	GA	TBA	TBA	161 386	200 m	60 m NS or EW	29 360	TBA	183: Aug 2016 p. 34	A contract with the preferred supplier is in the final stages of drafting by GA
Coonabarabran	GSNSW	GA	TBA	TBA	~50 000	250 m 60 m EW	11 000	TBA	TBA	184: Oct 2016 p. 23	The Quotation Request is in preparation by GA in collaboration with GSNSW

TBA, to be advised.

Table 2. Gravity surveys

Survey name	Client	Project management	Contractor	Start survey	No. of stations	Station spacing (km)	Area (km²)	End survey	Final data to GA	Locality diagram (*Preview*)	GADDS release
Stavely	GSV	GA	TBA	Est. 28 Nov 2016	Approx. 3465	200 m station interval along 14 traverses	TBA	TBA	TBA	The proposed survey covers parts of the Horsham, Hamilton, Ballarat and Colac Standard 1:250 000 map sheets. The survey is to collect gravity stations spaced 200 m apart on 14 separate road traverses.	A contract with the preferred supplier is being prepared by GA
Wiluna	GSWA	GA	Atlas Geophysics	21 Aug 2016	Approx 4454 in 2 separate areas	2500 m regular grid	103 000	21 Sep 2016	Nov 2016	184: Oct 2016 p. 24	The current survey covers the Nabberu, Wiluna and Sir Samuel Standard 1:250 000 map sheet areas. The survey completed data acquisition on 21 Sep 2016. The data were released via GADDS on 24 Nov 2016.
East Kimberley Airborne Gravity Survey	GSWA	GA	TBA	8 Oct 2016	38 000 line km	2500 m line spacing	82 690	TBA	TBA	184: Oct 2016 p. 24	The proposed survey covers the Medusa Banks, Cambridge Gulf, Lissadell, Gordon Downs, Mount Ramsay and Lansdowne standard 1:250 000 map sheet areas. The survey was 53.3% complete on 6 Nov 2016.
Daly Basin	NTGS	GA	Atlas Geophysics	13 Jul 2016	2537	Regular grid of 4, 2 and 1 km	35 730	6 Aug 2016	TBA	182: Jun 2016 p. 22	The data were released via GADDS on 21 Oct 2016
Coompana – PACE area	GSSA	GA	TBA	TBA	15 362	Regular grid of 2, 1 and 0.5 km	100 000	TBA	TBA	183: Aug 2016 p. 34	A quotation request is in the final stages of preparation

TBA, to be advised.

Table 3. AEM surveys

Survey name	Client	Project management	Contractor	Start flying	Line km	Spacing AGL Dir	Area (km²)	End flying	Final data to GA	Locality diagram (*Preview*)	GADDS release
Musgraves – PACE Area	GSSA	GA	CGG Aviation	18 Aug 2016	8489	2 km; E–W lines	16 371	The survey completed flying on 17 Sep 2016	Expected on 24 Nov 2016	179: Dec 2015 p. 23	The proposed survey covers parts of the Mann, Woodroffe, Birksgate and Lindsay Standard 1:250 000 map sheets
Musgraves – CSIRO Area	GSSA	GA	SkyTEM Australia	15 Sep 2016	7182	2 km; E–W lines	14 320	The survey completed flying on 13 Oct 2016	Expected early Dec 2016	179: Dec 2015 p. 23	The proposed survey covers parts of the Woodroffe, Alberga, Lindsay and Everard Standard 1:250 000 map sheets
Isa Region	GSQ	GA	Geotech Airborne	8 Aug 2016	15 692	2 km; E–W	33 200	The survey completed flying on 4 Nov 2016	TBA	182: Jun 2016 p. 23	The survey covers the Dobbyn, Cloncurry, Julia Creek, Duchess, McKinlay, Boulia and Mackunda Standard 1:250 000 map sheets. Additional work of approx. 1600 km was flown in late Nov in the Lawn Hill region

TBA, to be advised.

Geological Survey of South Australia: New state-wide grids available

A new gravity grid for South Australia has been produced using a ‘supervised variable density’ gridding method that utilised a GIS to classify the South Australian gravity station data into its optimal gridding resolution (Figure 1). This information provided the framework to manage and control a series of eight iterations of minimum curvature gridding to produce a virtually seamless 100 metre final grid, free of the gridding artefacts normally produced as a consequence of gridding regional data of variable density. The South Australian onshore and offshore ground and sea-borne gravity database was the dataset driving the interpolation while also utilising gravity station data from neighbouring states to eliminate edge effects. The data used for the interpolation comprises some 530 000 data points, extracted from a total of approximately 600 000 data points.

A new Total Magnetic Intensity (TMI) grid of South Australia was created by merging over 300 separate TMI grids from various eras and instruments. Similarly, new radiometric images of South Australia were created by merging over 1200 separate radiometric grids from various eras and instruments. The datasets used to create the magnetic and radiometric grids have been collected through numerous industry and Government exploration initiatives since the 1950s. Total Magnetic Intensity is measured in nanoTeslas (nT), and radiometrics are measured in ppm (Thorium and Uranium) and % (Potassium). Magnetic data are gridded at 35 metre cell size and radiometric data at 100 metre cell size. Interpretations should not be made a scales less than these.

All the grids are freely available via SARIG (sarig.pir.sa.gov.au). Use the Geophysical Data option under the Databases menu to select an area of interest and follow the prompts. A link to a zip file will be emailed to you. For assistance with SARIG, please don’t hesitate to contact Customer Services (resources.customerservices@sa.gov.au or 08 8463 3000).

Philip Heath, Tim Keeping, Gary Reed and Laz Katona
Geological Survey of South Australia
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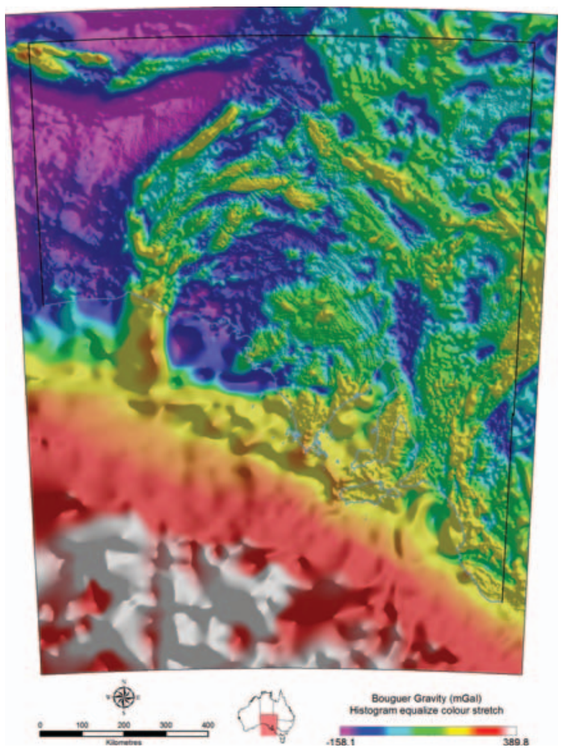

Figure 1. *The new gravity grid for South Australia.*

Geological Survey of Western Australia: East Kimberley 2016 regional aerogravity survey

The first airborne gravity survey to be contracted under the Western Australia Reconnaissance Gravity (WARGRAV2) Project is presently underway in the eastern Kimberley region of Western Australia.

The WARGRAV2 project — the subject of a National Collaboration Framework Agreement between the Geological Survey of Western Australia (GSWA) and Geoscience Australia (GA) — has the objective of completing 'generation 2' regional gravity coverage of Western Australia (see *Preview* issue 183, August 2016).

The East Kimberley 2016 airborne gravity survey area covers some 84 000 km^2 and encompasses much of the Halls Creek Orogen and parts of younger basins to the north and east (Figure 1).

The survey is being flown at a nominal height of 160 m above ground level along east–west lines at 2.5 km line spacing (25 km tie-lines). With an along-line spatial wavelength resolution[1] of 5 km or less, this configuration provides equivalent 2D spatial resolution with the 2.5 km grid of ground data that have been acquired from helicopter-assisted surveys in the southern and western parts of Western Australia since 2009.

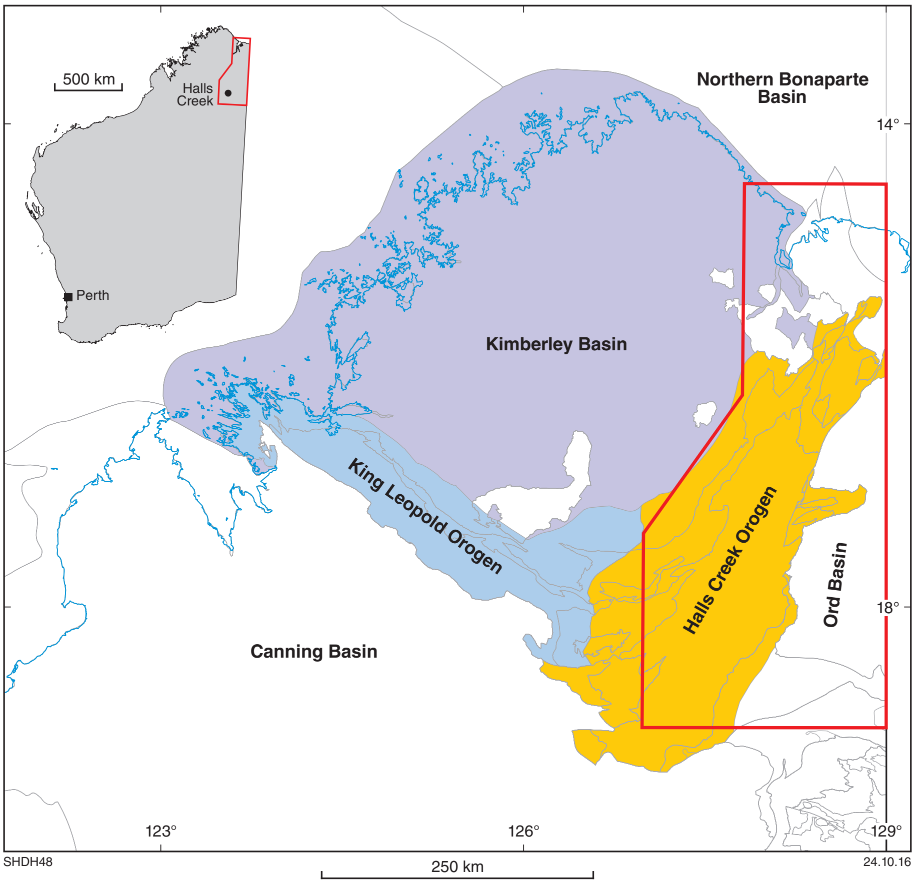

Figure 1. *Survey location relative to major tectonic units.*

Accuracy and precision

ISO 5725-1:1994(en) — Accuracy (trueness and precision) of measurement methods and results — Part 1: General principles and definitions. International Organization for Standardization; https://www.iso.org/obp/ui/#iso:std:iso:5725:-1:ed-1:v1:en

ISO 5725 uses the terms 'trueness' and 'precision' to describe the accuracy of a measurement method.

'Trueness' refers to the closeness of agreement between the arithmetic mean of a large number of test results and the true or accepted reference value. The measure of trueness is usually expressed in terms of bias, the total systematic error as contrasted to random error.

'Precision' refers to the closeness of agreement between test results. Precision depends only on the distribution of random errors and does not relate to the true value or the specified value. The measure of precision is usually computed as a standard deviation of the test results.

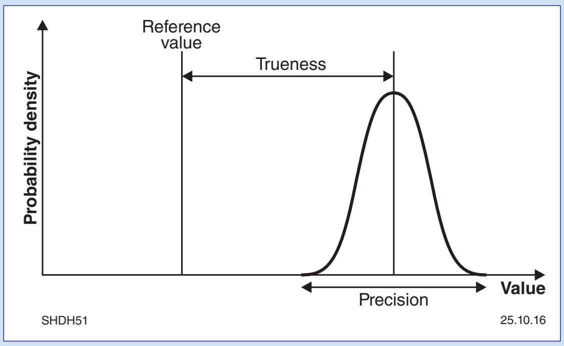

Figure is from https://commons.wikimedia.org/wiki/File:Accuracy_and_precision.svg

[1]The spatial resolution of a set of discrete, equally spaced, independent measurements (e.g. a ground gravity survey) is the distance between two measurements. The spatial wavelength resolution of the set is twice that distance. With oversampled data that are subjected to low-pass spatial filtering — as is typically the case in high-frequency data recording in an airborne gravity survey — we define the spatial wavelength resolution of the filtered dataset as the wavelength that has a gain of 0.5 (50% pass) in the filter gain spectrum. The spatial resolution is defined as half this distance.

The survey is funded by the Government of Western Australia as part of the government's Exploration Incentive Scheme. Contract tender and management services are provided by GA's Geophysical Acquisition and Processing Section.

The survey contract was awarded to Sander Geophysics following a public tender process that commenced in June 2016. Data acquisition commenced on 7 October and was completed on 4 December. Release of the data is anticipated in the first quarter of 2017.

The contract value of $1.12 million inclusive of tax (Commonwealth Contract Notice CN3380648; www.tenders.gov.au) for a nominal 38 000 survey line-km is equivalent to a cost of approximately $80 per '2.5 km ground station' for the 13 800 stations that would be required to cover the same areal extent with a 2.5 km helicopter-assisted survey grid.

On the plus side of this high relative cost is the ability to extend coverage offshore and over otherwise inaccessible areas. The cost must also be considered in the context of a regime in this region of Western Australia where obtaining ground access clearance is becoming increasingly expensive and time-consuming with increasingly large exclusion zones disrupting uniform data coverage.

In discussing survey accuracy, we follow the definitions of ISO 5725 which uses the general term 'accuracy' to refer to both 'trueness' and 'precision' (see inset). For this survey, the Sander Geophysics' AIRGrav gravimeter measurements are tied via a local survey base to Australian Fundamental Gravity Network station #1993929189 at Kununurra airport. Therefore, the values are 'true' by assumption and levelling so that accuracy equates only to precision.

The precision of the gravimeter measurements in static mode is being monitored by daily calibration tests at the survey base station. Survey inflight data precision is being estimated by multiple passes along a test line over a stretch of road along which ground measurements were made at 1 km spacing in 2011 and by comparison of survey line segments that coincide with ground survey points (Figure 2). The overall survey precision will be quantified by the standard deviation of the differences at tie-line and traverse line intersections.

The precision of airborne gravity surveys is less than that of ground surveys because the airborne gravity measurements are subject to more sources of variation. However, the lower precision is less critical at these 'regional interpretation scales' where small anomaly amplitude discrimination is less of an issue than for detailed surveys.

Figure 3 shows a comparison of the airborne data from a segment of a survey tie-line with ground data from a 1999 survey with 2 km station spacing.

For further information, contact geophysics@dmp.wa.gov.au.

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(With acknowledgements to Murray Richardson and Richard Lane at GA; John Brett at GSWA.)

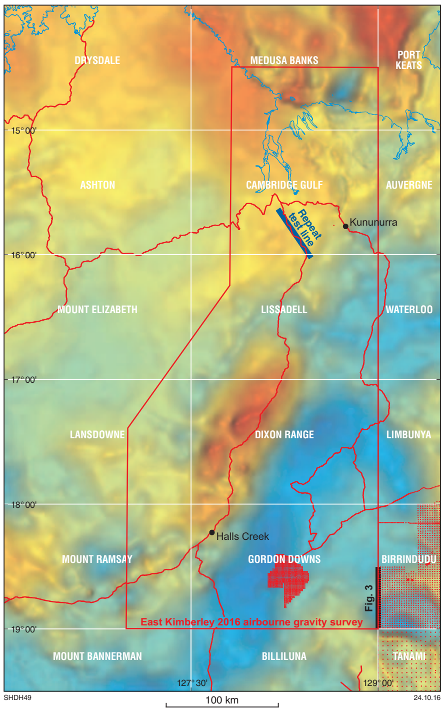

Figure 2. *East Kimberley 2016 airborne gravity survey area and test lines. Survey outline in red shown on background of 1:250 000 map sheet index and current Western Australian State compilation Bouguer anomaly grid based mainly on 11 km BMR data. Red dots are station locations of ground surveys with GA reliability rating of 5 or more that may be used for comparisons with the airborne survey data. Solid blue line west of Kununurra is survey repeat test line for estimation of inflight data precision (see text). Solid black line in southeast corner is line of ground and airborne profiles shown in Figure 3.*

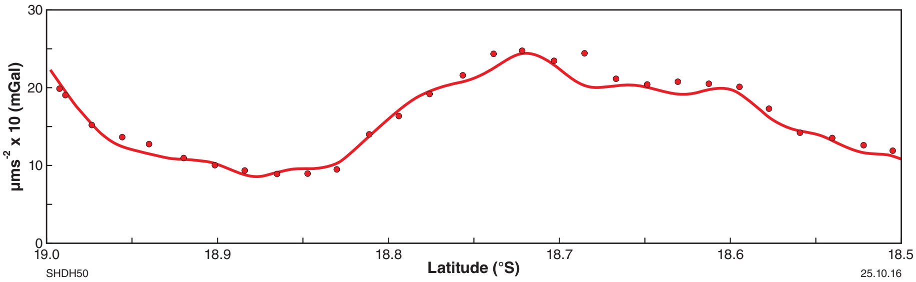

Figure 3. *Comparison of airborne data with ground data. Solid line is profile of field-processed airborne free air anomaly at 160 m AGL from segment of eastern boundary tie-line T109 along meridian 129E after filtering with 100 s low-pass filter (c. 5 km wavelength at 50% gain) — see Figure 2 for location; profile length is 55 km. Points are ground free air anomaly values from NTGS Tanami–The Granites Infill survey 1999 at 2 km spacing (publicly available from www.ga.gov.au/gadds); data have not been upward continued. The line of ground data points is located about 500 m east of the path of the airborne survey line.*

Canberra observed

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Government scuttles 'Marshall Plan' and instructs CSIRO to conduct long-term public good strategic research

Billed as an entrepreneur and Silicon Valley veteran, 54 year old Larry Marshall must have looked like a good choice in 2014 to take the 100 year old CSIRO into an age of innovation and digital applications.

However, he put the cat among the pigeons in 2015 when he cut the organisation's environmental and climate change programmes and handed out redundancies left, right and centre to world renowned scientists. His actions generated national and global protests because these cuts undermined Australia's international responsibilities to global treaties – as specified in CSIRO's enabling Act. Furthermore, they reduced our national capabilities to manage our land and sea resources.

How the CSIRO Board allowed this to happen, and why the previous Minister, Christopher Pyne, did not intervene is a mystery, particularly as CSIRO can be instructed by the Minister to undertake scientific research for 'any other purpose determined by the Minister'.

Fortunately, Minister Hunt did the right thing. He undertook a wide-ranging review and the result is a new Statement of Expectations for the organisation. On 19 November he announced that in the future: 'The paramount vision for CSIRO is to become the world's premier public research organisation over the coming decade and to apply its knowledge for the benefit of all Australians'.

The key priorities have been identified as:

- Pioneering in plant biology and agriculture.
- Enabling development of new research and technologies for human health, food and nutrition, and biosecurity.
- Leading climate change science, mitigation and adaptation research, including decadal forecasting as part of the work of the Climate Science Centre.
- Developing new environmental research and technologies for air, land, water and oceans.
- Collaborating with industry to help sustainably manage our resources, mining equipment and energy sectors.
- Collaborating across the research community to maintain and build our astronomy capability.
- Collaborating with industry to help develop our advanced manufacturing capabilities.
- Collaborating with industry to improve Australia's digital and data management capabilities.

This is a completely different approach to Larry Marshall's focus on short-term start-up research companies and it sets a solid basis for the future

The Minister also encouraged CSIRO to develop additional priorities based on its engagement with staff and the broader community, including industry and academia.

As Minister Hunt stated:

> *These outcomes will continue to improve Australians' quality of life with better health, food production and quality, environmental resilience, and economic capability., and:*
> *To assist in achieving this, staffing levels will rise and funding for CSIRO will increase from $1.35 billion to $1.465 billion over the next four years.*

This is a completely different approach to Larry Marshall's focus on short-term start-up research companies and it sets a solid basis for the future. Why the CSIRO Board extended Marshall's appointment earlier this year for a further term, when his core policies were likely to overturned by the Minister, is another mystery.

Education matters

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Lightning strikes at ASEG (Vic branch) Student Night

RMIT PhD student Lachlan Hennessy gained first prize at the Victorian Branch Student Night presentations, with a talk on 'Magneto-tellurics with lightning source information'. The method promises improvements in audio-magneto-telluric studies investigating depths to 500 m, by reducing recording time and increasing signal to noise ratios for the AMT method.

ASEG Branch President Seda Rouxel presents a cheque for first prize to Lachlan Hennessy.

Other presentations were given by:

Elizabeth Grange (MSc – University of Melbourne): 'A new interpretation of the Lachlan fold belt', Jesse Keegan-Osborne (Hons – Monash University): 'Emplacement of the Stawell granite', Andrew Pearson (MSc – University of Melbourne): 'The structural evolution of the Wentworth trough', Hamish Stein (MSc – University of Melbourne): 'Shallow elastic property models for the North-west Shelf', with Jesse and Hamish sharing the runner-up prize.

Asbjorn Christenson, speaking for the judging panel, said 'We were very impressed with the breadth of the presentations, and it's obvious that a lot of work has gone into the preparation of these talks'.

Contestants at the Victorian ASEG Student Night; from left, Jesse Keegan-Osborne, Hamish Stein, Elizabeth Grange, Andrew Pearson and Lachlan Hennessy.

Student projects in geophysics completed in 2016

Queensland

PhD

Shaun Strong, University of Queensland: 'Resolution Enhancement in Shallow 3D-PS Seismic Reflection'.

This thesis aims to advance methodology for acquiring and processing 3D multicomponent seismic data for shallow (<300m) exploration targets. The primary focus is to improve seismic resolution, and hence geological interpretation, for coal-scale targets.

The coal industry is a significant contributor to the energy security and economy of Australia and the world. Conventional P-wave seismic methods are widely used in this industry, providing economic, safety and environmental benefits. There is potential for expanding these benefits by including multicomponent procedures. In this thesis, the primary focus is on converted-wave (PS) reflection, which is a logical extension to the standard approach. This has theoretical potential to provide extra geological information. It has also been proposed that there may be resolution advantages for shallower targets such as coal.

A valuable starting point for understanding resolution in shallow P and PS reflection is via visco-elastic finite-difference simulation. This provides a useful indication of the reflection response of different targets, and can include the influence of different processing flows. For typical coal-scale environments, modelling with reasonable anelasticity assumptions suggests that PS resolution is unlikely to be superior to P resolution, even with idealised acquisition and processing. In real-world situations, achieving good PS resolution may be even more challenging. There are a number of factors across the acquisition and processing flow which incrementally influence resolution.

Survey design is intrinsically more complex for PS surveys than for P, primarily because of ray-path asymmetry. In addition, phase and amplitude effects require careful analysis, and finite-difference modelling provides a useful tool. Such modelling suggests that for shallow surveys in particular, it may be possible to incorporate longer relative offsets, compared to the petroleum scale. An examination of bin fold, and offset/azimuth distribution, suggests that the natural bin size of a PS survey is mostly dependant on the receiver spacing, and is generally larger than for P waves. This favours the use of higher receiver densities for multicomponent surveys. These observations can be more important at the shallow scale, again because of greater ray-path asymmetry and potentially higher VP/VS ratios.

One of the most critical steps in shallow PS processing sequence is correcting for the S-wave receiver statics. Three relatively conventional approaches have been evaluated. A surface-consistent inversion approach has been shown to fail for shallow targets, or in the presence of strong noise. For our 3D data set, PPS refraction analysis provided the preferred solution. In other cases where PPS refractions are poorly defined, our robust statistical approach may be useful for determining short-wavelength statics, although additional long-wavelength control would then be needed.

In exploration seismology, surface waves are commonly considered to be noise. However, the dispersive nature of surface waves is strongly dependent on the S-wave properties of the near surface. These properties can be estimated using the so-called MASW technique. Most commonly, MASW has been applied in an engineering context. Using modelling, and a high-resolution 2D dataset, we have evaluated the viability of extracting surface-wave dispersion information from shallow exploration data, where parameters are not necessarily ideally suited to the task. This suggests that viable S-wave velocities (and potentially S-wave statics) can be derived using exploration equipment provided receiver intervals are less than about 10 m. It has also been demonstrated that this method can be used with a Vibroseis source, and that use of uncorrelated data provides improved low-frequency response.

Application of the same approach to a real, coal-scale 3D dataset has been more difficult, partly due to the coarser geophone spacing (15 m). However, incorporation of an interferometric approach shows potential for providing broad-scale shallow S-wave velocities. In particular, for our trial 3D dataset, a combination of robust statistics (short-wavelength) and dispersion (long-wavelength) provides a useful alternative to the preferred PPS refraction statics approach.

Analysis of our high-fold 3D multicomponent dataset has included a preliminary investigation of azimuthal anisotropy. A pragmatic assessment of the PS stacking velocity for the target reflector indicates significant azimuthal variation in an 'effective' VP/VS ratio. In the vicinity of major faults, anisotropy of about 5% is indicated. The observations are consistent with azimuthally varying VP, along with S-wave splitting effects, with higher velocities in the direction perpendicular to fault planes. This could be an indication of fracturing associated with local stress fields. More detailed research is required to validate these preliminary results, and to assess the degree to which correction for azimuthal velocities can improve stack resolution.

A significant proportion of usable PS energy can be on far offsets. This may be particularly so for shallow surveys. These far offsets tend to be susceptible to NMO stretch during conventional processing, and this has a significant impact on the resolution of shallow PS data. Use of a non-stretch moveout method, including higher-order polar-anisotropy terms, greatly improves the resolution of the stack data in coal-scale environments.

Imagery of coal-scale targets can benefit by integrating PS reflection with the standard P-wave product. This research has demonstrated that achieving good PS resolution is challenging, and requires careful consideration of multiple factors in the design, acquisition and processing chain. The range of methodologies demonstrated here will further advance the practical application of PS reflection at the coal scale.

M.Phil

Alan Meulenbroek, University of Queensland: 'Inversion of Seismic Refraction Amplitudes for Near-Surface Velocity Control'.

Analysis of seismic refraction amplitudes has the potential to produce a richer geological interpretation than if only travel-times are considered. In theory, the amplitude of a seismic head-wave is dependent on the strength of the shot and the offset at which it is measured. A constant of proportionality, called the head-wave coefficient, is a function of the elastic properties either side of the refracting interface. As the velocity contrast between the two media decreases, the head-wave coefficient increases.

A detailed examination of refraction amplitude theory reveals that the head-wave coefficient is a product of two Zoeppritz transmission coefficients, a downgoing one at the source end and an upgoing one at the receiver end. The bulk amplitude of the head-wave coefficient is mainly due to the transmission coefficient at the receiver end. However, the receiver component is relatively insensitive to lateral changes. On the other hand, the transmission coefficient at the source end is sensitive to lateral changes.

Theoretical models, which simulate laterally inhomogeneous geologies, are used to forward-model refraction amplitudes. The head-wave coefficient is then estimated via non-linear inversion of refraction amplitudes. Inverted shot and receiver terms are shown to be related to the transmission coefficients at the shot and receiver ends. The product of the inverted shot and receiver terms are related to the full head-wave coefficient. The inversion cannot separate the effect of velocity contrast from short-wavelength shot/geophone coupling effects. Smoothing of the inverted solution is suggested as a means of reducing coupling effects.

For laterally inhomogeneous models, offset limiting is required prior to inversion in order to achieve successful separation of constituent amplitude components. For offset-limited model data, the estimated model parameters exhibit consistency with the true model parameters in a relative sense. Non-uniqueness between parameter groups prohibits successful estimation of model parameters in an absolute sense. Calibration is therefore required to adjust the relative results obtained from inversion to results which are consistent with geology. This calibration uses independent estimates of weathering-layer velocity at several points along the seismic line. Calibration can be performed on the inverted shot terms alone, or the product of the inverted shot and receiver terms.

The inversion methodology is evaluated on three real data sets. For the first Vibroseis dataset, the relative head-wave coefficient profile is consistent with that derived using an alternative approach (the Refraction Convolution Section). However, the implied weathering-layer velocity profile differs from that estimated by analysis of direct arrivals.

For the second Vibroseis dataset, the derived weathering-layer velocity is reasonably consistent with the long-wavelength velocity profile derived from analysis of hammer shot records, acquired as part of the original survey. The CMP stack, incorporating the velocity profile from refraction amplitudes, shows subtle structural differences when compared to the conventional stack.

The third dataset, which uses dynamite as a source, exhibits large variations in source strength. A velocity profile is not derived because these large source effects swamp any amplitude changes related to velocity changes at the refractor.

For these real-data tests, offset limiting does not assist separation of the shot and receiver terms (as was the case for the model data). Independent statistical analysis of average shot and receiver amplitudes suggests that the inversion process itself is working correctly.

However, it appears that in practice, observed refraction amplitudes are strongly influenced by factors not included in theoretical models. Further work is required before this technique can provide a reliable tool for near-surface characterisation.

Honours

Shakira Heffner, University of Queensland: 'Analysis of azimuthal anisotropy in coal-scale 3D seismic reflection'.

Azimuthal anisotropy in seismic velocity is a well-known phenomenon, although it is often ignored in conventional reflection processing. Such anisotropy can result from sub-vertical fracturing often related to orientation of horizontal stress. It can also be an artifact of dipping interfaces in an isotropic system.

Some understanding of the likely contributions can be obtained from simple numerical models. If dips are less than 10 degrees, then spurious azimuthal effects are likely to be less than 2%. If reasonable values of Thompson parameters are assumed, true velocity anisotropy can be well in excess of 10%. If this is ignored in the NMO process, then smearing is expected, particularly at the coal scale where dominant frequencies in excess of 100 Hz can be expected.

A robust algorithm has been implemented to invert reflection travel times in terms of an azimuthally anisotropic velocity model. The inversion yields the fast azimuth (major axis of best-fit ellipse) and the degree of anisotropy (derived from the ellipticity). The algorithm performs well on a high-fold 3D P-wave survey from the Bowen Basin. A very consistent pattern of azimuthal anisotropy is observed across the survey area, with largest magnitude approaching 10%. The observations cannot be explained in terms of known dip and are believed to represent true azimuthal effects. A preliminary analysis of an associated converted-wave survey suggests anisotropy parameters (magnitude, direction) which are consistent with the P-wave results. When the detected anisotropy is allowed for in the NMO correction, the improvement in stack quality is not as significant as expected based on modelling. For these shallow data, factors such as NMO stretch and statics are significant and it is possible that such effects are overriding improvement achieved via anisotropic NMO.

Christopher Mathews, University of Queensland: 'Near-Surface Characterization from Dispersion of Rayleigh and Love Waves'.

Surface wave dispersion has been exploited in earthquake seismology since the 1920s, and for several decades in engineering seismology. Until very recently, seismic reflection surveys have treated surface waves as noise, to be attenuated by acquisition design and in processing. This study investigates the properties and underlying characteristics of surface-wave dispersion, and assesses practical potential in various exploration-scale scenarios. In the engineering and exploration contexts, most studies of dispersion have exploited Rayleigh waves, because of the ready availability of vertical-component recording equipment. This study focusses on the possible advantages of combined analysis of Rayleigh and Love waves, using 3C recording.

Propagator-matrix algorithms have been implemented for both Rayleigh- and Love-wave dispersion. Theoretical dispersion curves illustrate sensitivity to various physical properties of near-surface earth models. While Rayleigh-wave dispersion is primarily influenced by S-wave velocities, it can also depend significantly on P velocity. Love waves have the advantage that dispersion is totally independent of P velocities. This theoretical analysis also demonstrates that interpretation of higher modes is likely to be much simpler in the case of Love waves.

This study examines different approaches to extracting dispersion curves, and performing inversion, for real exploration-scale data. One important limitation is the attenuation of low frequencies due to geophone response and short recording time. This reduces the reliability of inverted earth models at sub-weathering depths. The study also demonstrates the problems arising from stacking of dispersion curves in situations where geology varies laterally. Where it is feasible to acquire 3-component data, best results are obtained by performing joint inversion using both Love and Rayleigh dispersion curves. Although reflection acquisition parameters may not be ideal for dispersion analysis, it is nevertheless possible to extract meaningful near-surface velocity information. This may have direct geological value, and provide additional control in statics solutions.

Tasmania

Honours

Brady Gower, University of Tasmania: 'Structural and Sedimentological Analysis of the Adele Trend – Browse Basin'.

The Adele 3D seismic survey in the Caswell Sub basin of the Browse Basin, offshore northwest Western Australia, depicts a sequence of sediments above Proterozoic basement that range from late Palaeozoic rift sequences to passive margin sediments of the Pliocene-Recent Barracouta Formation. This study evaluates the structural and sedimentological architecture of the region, with a particular emphasis on the stratigraphy above the Callovian unconformity.

Faults in lower stratigraphic units are predominantly oriented NE-SW but in upper stratigraphic units the dominant trend is E-W. This observation is consistent with stress orientations previously inferred for major basin forming events that have affected the northwest shelf of Australia since the Late Palaeozoic. An archetypical example of strata-bound polygonal fault systems is developed within fine grained strata of the Upper and Lower Heywood Formations. A prograding deltaic sequence characterised by the presence of clear clinoform reflectors has been identified and mapped beneath the Puffin Formation throughout the survey area. The isochron map of the deltaic interval suggests that this sequence potentially provided a control on the deposition of the overlying Puffin Formation. The Puffin Formation is an important petroleum exploration target formation within the Caswell Sub Basin which is delineated on the basis of time-structure and isochron maps that illustrate exploration targets associated with existing petroleum wells. Sedimentary units deposited during the mid to late Miocene were deposited in a tropical carbonate system, and are associated with widespread karstification features developed during sea-level lowstands.

The fine grained sediments of the Heywood Formation can form a regional seal but recognition of complex polygonal fault systems within this interval has implications for the integrity of underlying petroleum systems, as significant small displacement faults could dramatically increase the permeability of normally impermeable sediments. Sand packages within the deltaic sediments of the Fenelon Formation have potential as hydrocarbon reservoirs. Palaeokarst features in the Bassett Formation pose a significant risk when drilling exploration wells. The increased porosity and permeability of karstified formations can lead to drilling mud losses, as well as borehole collapse.

Declan D. G. Radford, University of Tasmania: 'Geological mapping from radar imagery with machine learning'.

Mineral exploration and geological mapping in the highly prospective region of western Tasmania is difficult due to the combined effects of steep topography, dense vegetation and limited outcrop. The potential for imaging radar to be beneficial for geological mapping in this region is significant as the microwave signal is able to penetrate vegetation canopies and image the surface. When radar is analysed in combination with other sources, such as geophysical and Light Detection and Ranging (LiDAR) data, a wider range of lithological related signals are captured allowing a more comprehensive geological interpretation to be created. Machine learning algorithms are well suited to integrating and classifying data such as these for the production of objective geological maps.

Analysis of the radar imagery highlighted the importance of image texture and the identification of boundaries for geological classifications. Field work showed that the majority of anomalous geological features identified within the radar imagery related to geobotanical and geomorphological relationships. The inconsistent nature of these relationships limits the reliability of the radar method to determine lithology.

The supervised machine learning Random Forests (RF) classifications, based on geophysical data, were accurate (~ 90%) even when using a very limited training data input size (~ 0.25% of the total data). RF successfully identified a new region of the Tasmanian mafic-ultramafic complexes that was validated through targeted field work. This discovery has significant tectonic implications with respect to western Tasmanian geology, providing insight into the Cambrian subduction zones, Tyennan Orogeny as well as the relationship between Gondwana and the Cambrian Tasmanian.

Ultimately the results from the RF classifications and field observations have been efficiently combined with geophysical and radar data to produce a new geological interpretation of the Heazlewood region. This research further validates the growing application of machine learning to solve geoscience problems, particularly in remote and difficult terrain.

Tyler Williams, University of Tasmania: 'Seismic Evaluation of the Integrity of the Henty Tailings Storage Facility, Henty, Tasmania'.

Traditional geotechnical methods such as the Cone Penetration Test (CPTu) measure shear-wave velocity (V_s) which provides a proxy for material strength. These invasive methods are costly and time consuming, and thus inefficient for characterisation of large areas. The Multi-Channel Analysis of Surface Waves (MASW) technique can be utilised to rapidly evaluate the geotechnical properties of near-surface materials to non-invasively estimate vertical variations in V_s. V_s correlates directly with liquefaction resistance, and hence it is possible to estimate the potential for soil liquefaction through the analysis of surface waves. This study applies the MASW method to assess the geotechnical properties and liquefaction potential of the Henty Mine tailings dam in western Tasmania prior to a planned upstream raise of the dam embankment. The results of MASW assessment are compared to limited data acquired using CPTu testing.

Five MASW traverses were conducted at the Henty Tailings Storage Facility (TSF) and 1D vertical estimates of V_s derived from inversion of surface wave dispersion were used to produce 2D V_s sections for each traverse. Four traverses were conducted perpendicular to the embankment to highlight V_s variations within the dam construction materials and tailings. A single long traverse was undertaken parallel to the embankment to highlight lateral variations in the tailings that will partially act as the foundation for the proposed upstream raise. MASW V_s estimates were compared to CPTu V_s values to assess the accuracy of V_s values derived from the inversion of surface wave dispersion data.

MASW provides layered 1D V_s profiles which integrate the response over the length of the seismic spread (78 m). The MASW V_s profiles have low vertical resolution when compared to CPTu data but effectively capture the general variations in V_s. MASW V_s data were used to calculate values for the probability of liquefaction (P_L%), which were used to generate 2D profiles of a deterministic Factor of Safety (FS). These FS profiles suggest that the tailings material beneath the proposed upstream lift will provide a suitable foundation for construction and will require only a small amount of additional preparation. Near surface zones of high P_L % and low FS are present further into the TSF and these zones will acquire additional investigation if later upstream lifts are intended.

The MASW technique is a cost-effective method for lateral imaging of V_s in mine tailings dam environments. MASW estimates cannot provide the high-resolution V_s data obtained using CPTu but does provide continuous measurements between CPTu locations that can reduce uncertainty and be used to provide probabilistic assessment of liquefaction potential.

Victoria

Honours

Josephine Bailey, Monash University: 'The structure and emplacement of the Two-Eyed Creek granodiorite and Bulgana diorite'.

In this study, Anisotropy of Magnetic Susceptibility (AMS) and the gravity surveying and forward modelling methods are used in conjunction with field observations and petrography to define the structural, petrological, petrophysical and geophysical characteristics of the eastern half of the composite Stawell pluton (Stawell Zone, Western Lachlan Orogen). This half of the pluton, consisting of the Two-Eyed Creek Granodiorite and Bulgana Diorite, is characterized by a tail-shaped map pattern. This multi-disciplinary approach has characterized the structure of the two intrusions, and provided insights on their mode of emplacement. Magnetic directional data from the AMS study reveal magnetic foliation and lineation patterns, which are confirmed by petrological observations to represent a primary emplacement-related magmatic fabric. This fabric indicates NE-directed magma flow along the 'tail', originating from a feeder zone underneath the center of the composite pluton, the location of which is inferred via the interpretation of gravity data. Forward modelling suggests the 3D geometry of the intrusions is that of a tongue-shaped lobe. The orientations of fractures and syn-plutonic dykes suggest a potential structural control on intrusion by NW-SE extensional reactivation of the Early South Faults in the early Devonian.

Jesse Keegan-Osborne, Monash University: 'Emplacement of the Stawell Granite as determined by combined use of gravity and AMS'.

A hybrid laccolithic and lopolithic geometry is inferred from geological and geophyisical data for the Stawell granite. Nearly circular in shape, the 13 km diameter Stawell granite is the youngest of three phases of the teardrop shaped, E-W trending Stawell pluton, and lies 2 km east of the Western boundary of the Lachlan Fold Belt. Magnetic fabric determined by anisotropy of magnetic susceptibility has been inferred to correlate with the magmatic fabric by use of microstructural observations and mineral orientation analysis. Magnetic foliations are concentric around a central feeder zone and dip outwards. Magnetic lineations radiate away from the central feeder zone and plunge outwards. Gravity data suggest that the granite is roughly tabular with a deeper zone in the southern part of the granite with a maximum thickness of 4 km, and a central northern root zone. The granite is interpreted as post kinematic and as being emplaced differently to the earlier phases of the pluton.

Adriana Traviati, Monash University: 'The Evolution and Development of the Barracouta Region, Gippsland Basin, Australia'.

The Barracouta field, discovered in 1965, is one of the most significant gas fields in Australia. It is located in the offshore Gippsland Basin, one of Australia's most prolific hydrocarbon provinces. This study aims to determine the structural and stratigraphic evolution of the Barracouta region, assess major stratigraphic packages, interpret major fault sets, analyse the major N-1 gas and M-1 oil reservoir and seal characteristics and finally assess the remaining hydrocarbon potential of the Barracouta field. This involves interpreting stratigraphic units and biostratigraphic seismic marker horizons in three dimensions across the field area, as well as undertaking a regional fault analysis at depth, correlating well log responses and mapping the movement of the gas–water contact to its position at 2001. It also involves investigating key characteristics of the N-1 and M-1 reservoirs and their seal properties, constructing a burial history plot to determine the depositional history of the field, performing a depth conversion across the 3D dataset and finally undertaking a volumetric analysis of remaining reserves. This study draws upon the G01a 3D seismic volume acquired in 2001, well logs across 13 wells, government data and well completion report data.

The research demonstrates how post-Latrobe Group sediments have been deposited syn to post compressionally over the Barracouta anticline. It highlights the presence of two major Early and Late Cretaceous fault sets and shows that the Barracouta field's anticlinal structure was formed by the preferential re-activation of an ~E–W trending Early Cretaceous normal fault set caused by an Early Miocene compressional event that led to structural inversion. The major reservoir–seal couple relationships and properties change across the field in their thickness and lateral distribution, with most reservoir–seal couples being thickest at the centre west of Barracouta.

The study shows that the 2001 gas–water contact can be imaged via amplitude extraction and spectral decomposition methodology, showing a movement of ~42 m over 36 years of production from a position of 1151 m TVDSS at first production in 1965 to 1109 m TVDSS as at 2001. Finally, the volumetric analysis indicates that ~1.15 Tcf has been produced in this interval, with ~0.7 to 0.9 Tcf remaining to be produced as at 2006, according to deterministic and estimated volumetric calculations.

South Australia

Honours

Hugh Merrett, University of Adelaide: '2D Lithospheric Imaging of the Delamerian and Lachlan Orogens, Southwestern Victoria, Australia from Broadband Magnetotellurics'.

A geophysical study utilising the method of magnetotellurics (MT) was carried out across southwestern Victoria, Australia, imaging the electrical resistivity structure of the lithosphere beneath the Delamerian and Lachlan Orogens. Broadband MT (0.001–1000 Hz) data were collected along a 160 km west-southwest to east-northeast transect adjacent to crustal seismic profiling.

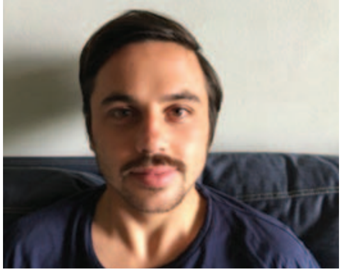
Phase tensor analyses from MT responses reveal a distinct change in electrical resistivity structure and continuation further southwards of the Glenelg and Grampians-Stavely geological zones defined by the Yarramyljup Fault, marking the western limit of exploration interest for the Stavely Copper Porphyries. The Stawell and Bendigo Zones also show change across the Moyston and Avoca faults, respectively.

Results of 2D modelling reveal a more conductive lower crust (10-30 Ωm) and upper mantle beneath the Lachlan Orogen compared to the Delamerian Orogen. This significant resistivity gradient coincides with the Mortlake discontinuity and location of the Moyston fault. Broad-scale fluid alteration zones were observed through joint analysis with seismic profiling, leaving behind a signature of low-reflectivity, correlating to higher conductivities of the altered host rocks. Isotopic analysis of xenoliths from western Victoria reveal the lithospheric mantle has undergone discrete episodes of modal metasomatism. This may relate to near-surface Devonian granite intrusions constrained to the Lachlan Orogen where we attribute the mid to lower crustal conductivity anomaly (below the Stawell Zone) as fossil metasomatised ascent paths of these granitic melts. This conductivity enhancement may have served to overprint an already conductive lithosphere, enriched in hydrogen from subduction related processes during the Cambrian. A predominately reflective upper crust exhibits high resistivity owing to turbidite and metasedimentary rock sequences of the Lachlan Orogen, representative of low porosity and permeability. Conductive sediments of the Otway Basin have also been imaged down to 3 km depth southwest of Hamilton.

NSW

Honours

Bailey Payten, The University of Sydney: 'Modelling the fragmentation of cordilleran orogens: Applications to the Lord Howe Rise'.



The fragmentation of Eastern Gondwana led to the formation of the world's largest continental ribbon, the Lord Howe Rise. This fragmentation occurred through west-dipping subduction of the Pacific plate and subsequent back-arc extension in the Eastern Gondwana Cordillera; the mechanisms of which are not well constrained. Through thermo-mechanical numerical modelling, this study explored the impacts of the Cordillera itself, a buoyant mantle wedge and kinematic plate movement on back-arc extension and subduction.

A palinspastic reconstruction of the Lord Howe Rise and Eastern Australian margin was performed, with reconstructed extensional velocities, crustal thicknesses and crustal geometries derived for comparison to the numerical model output. Presence of a Cordillera introduces a gravitational potential energy anomaly resulting in orogenic collapse which then promotes trench retreat. Removal of this orogen caused a ~60 km decrease in continental extension. Introducing a buoyant mantle increases continental extension by ~70 km through development of higher stresses promoting lateral extension in the overriding continental crust. Most importantly, the study found that removing horizontal oceanic plate velocity to develop increased extension by ~90 km, with continental crust hyperextension and asymmetry matching the narrow Eastern Australian margin and hyperextended Lord Howe Rise. Rift migration is proposed to be the primary factor that controlled the formation of this crustal geometry.

Western Australia

MSc

Adouley Guirou, Curtin University: 'Extraction of Induced Polarisation from Magnetotelluric measurements, case study from Atlántida Copper-Gold deposit, Atacama Desert, Northern Chile'.

Retrieving induced polarisation effects from natural source magnetotelluric or natural field induced polarisation (NFIP) surveying continues to be a subject of considerable interest to the geophysics community. The complex electromagnetic response of a finite body is caused of induction and polarisation in the body and by the distorted inductive current of the background medium. At low enough frequencies (below the 'DC limit'), the induction currents are negligible and the polarisation effect is dominant. Since the dc response is not frequency dependent, any frequency dependent conductivity change at low frequencies is due to polarisation effect. The frequency dependent conductivity (or resistivity) changes at low frequencies (below 'dc limit') can be expressed by the percent frequency effect (PFE). Normalised phase and imaginary component of electric field with respect to a reference field measurement are used to express the polarisation effect.

The NFIP technique was applied on the induced polarisation (IP) anomalous Atlántida copper-gold deposit in Chile. The resulting NFIP laterally correlates with conventional induced polarisation. The possibility to retrieve induced polarisation from magnetotelluric brings two significant advantages: firstly, the possibility of using magnetotelluric measurement in difficult terrain to observe resistivity and chargeability distribution and secondly, the possibility to explore for deep seated targets where conventional IP systems have limitations.

Abdulaziz Aljaroudi, Curtin University: 'Optimal Seismic Acquisition Parameters Design, Data Processing and Imaging, using 2D Finite Difference Modelling of the Complex Geological Structures'.

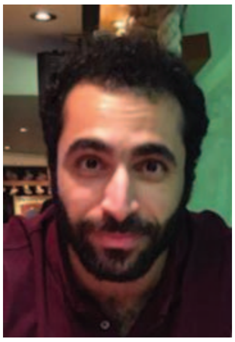
The project consists of the two-dimensional complex structure(s) embedded within the different geological environment created in painting software in grayscale mode. These geological environments are varying from simple to complex one. Then, four different standalone programming codes are used to convert the painted model from raw picture format to field format disk (SEG-Y) that is readable by Promax. The SEG-Y tape that contains the model is transferred into an interval velocity in-depth model for modelling and migration analysis.

The finite-difference method has been effectively applied to a better understanding of the seismic wave propagation through the created models. This has been accomplished by generating synthetic zero-offset seismic sections using exploding reflector and source point modelling. Later, various migration algorithms on these seismic sections provided different outcomes, and their performance depends on many factors. The main difficulty of the seismic imaging is the target of a complex structure (2D selfie) in created models, with distance (x) of 1000–3000 meter and a depth of 1200–3000 meter. This thesis addresses three issues in seismic imaging: (1) The stability of various migration approaches in handling laterally varying velocities; (2) Speed and accuracy of migration algorithms; and (3) Computational time comparative analysis of various migration algorithms.

This thesis describes the implementation of four different migration algorithms on the exploded reflector models and normal source models: Kirchhoff time/depth migration, Stolt migration and Explicit FD migration. These various implantations yield to a least to precise imaging accuracy in complicated structure(s) in the models. Stolt was fastest migration implementations and was able to image the constant velocities areas to mild laterally and vertically variant velocities accurately, but it fails in areas where there is a very large contrast in velocity. On the other hand, the main advantages of Kirchhoff depth migration over Stolt migration and Kirchhoff time migration are its ability to handle lateral velocity variations with comparable efficiency. It has seen that Kirchhoff depth migration can be no more accurate, at least for moderate dips, than the finite difference methods which also has higher quality migrated images. The computational time amount of theses migration algorithms is directly proportional to the seismic migration algorithm used, amount of processed data, and frequency content of the seismic data involved, as well as adequate buffer size, allocation of memory in seismic migration algorithms, and particular migration operator performance (i.e. Stolt factor, maximum dip calculation, travel time solver, etc.).

Given its content, this thesis can be a handy manual for new seismic imaging users, as it can give them knowledge of what can be expected from the modelling and various migration algorithms, applied on different geological environments. The results of created six models are the following: 144 post-stack data sets with different CDP spacing and frequency content, 18 pre-stack data with different frequency content, and more than 642 migrated images and special migration tests.

Abdulrahman Al Jaafari, Curtin University: 'Geophysical characterization of landslides in Serbia and Bosnia and Hercevgovina – a GWB project'.



Landslides are considered one of the main problems in Serbia and Bosnia & Herzegovina (BiH). The locality investigated in this research is near the city of Lopare. Landslides in this area are particularly devastating as they appear to be the result of liquefaction of sand caused by heavy rainfall. Landslides here were investigated by a combination of seismic and resistivity data. Seismic investigations utilized reflection, refraction and surface waves. The methodology known as Multi-Channels Analysis of surface waves (MASW) was used to invert for shear wave velocity along reflection profiles. The output of each individual method is initially analysed. Final analysis utilized joint interpretation of these diverse data sets. The main body of the landslide is well defined by the reflection method. Its internal composition is characterized by low shear wave velocity and resistivity values.

Nicolas Galindez Carrasquero, Curtin University: 'Comparative advantages and disadvantages of using two different source geometries in the North-West Shelf'

Honours

Petr Lebedev, Curtin University: 'Cloud based cooperative magnetotelluric and seismic inversion'

Christian Proud, Curtin University: 'Modelling-driven workflow for 3D seismic inversion for Stage 2C of the Otway Project'.

Seismic inversion refers to a group of methods which aim to convert recorded seismic amplitudes into properties of the subsurface. Seismic inversion has many input parameters, many of which have uncertainty that affects the resulting subsurface models. Uncertainty analysis can therefore be a time-consuming task. Many studies fail to quantify sensitivity and accuracy of seismic inversion in realistic scenarios. They utilise oversimplified subsurface and noise models. To quantify the sensitivity and accuracy of post-stack and pre-stack seismic inversion we use full-Earth static models and synthetic seismic data derived from these. Parameters were varied one at a time and various statistical measures were used in quantifying the accuracy and sensitivity. We found that pre-stack simultaneous inversion when inverting for P-impedance was less sensitive than post-stack inversion. The accuracy of pre-stack simultaneous inversion was superior to that of post-stack inversion producing on average 30% lower root-mean-square error. This increased accuracy is thought to be due to the increased bandwidth of the extracted angle-dependent wavelets compared to wavelets extracted from post-stack data. Whilst angle-dependent wavelets are most sensitive to changing parameters the pre-stack algorithm appears to be more robust in the presence of noise. Understanding and quantifying inversion sensitivity and accuracy allows us to focus research into accurate determination of only the most influential parameters into inversion.

Kristopher James Wright, Curtin University: 'Palynological and geophysical analysis of the stratigraphy and palaeoenvironmental context of a palaeovalley near Mulga Rock, Western Australia'.

The stratigraphy and palaeoenvironmental context of Vimy Resources Ambassador lignite-hosted uranium deposit in the Narnoo palaeovalley at Mulga Rock has been evaluated to determine if there is a correlation between changes in palynoassemblages and seismic characteristics. The Narnoo palaeovalley is a Cenozoic inset-valley within the southern Proterozoic Officer Basin and is located 240 km ENE of Kalgoorlie.

Prior to this study the lignites and carbonaceous clays were dated as late Eocene, and a trial seismic survey was conducted over the East and West Ambassador prospect areas, now excavated as geotechnical trenches. In total, 31 samples were collected and palynologically processed from six boreholes along the seismic lines. Sixteen lignite and carbonaceous clay samples from three East trench boreholes were palynologically analysed and dated as late Eocene on the presence of restricted index species *Proteacidites nasus*, *Tricolpites incisus*, *Anacolosidites acutullus*, *Proteacidites reticulatus* and *Proteacidites rynthius*. The two lithological units were palynologically distinguished by changes in abundance of major palynomorph groups, with *Haloragacidites harrisii* prominent in the lignitic unit and *Proteacidites* and *Myrtaceaidite*s species prominent in the carbonaceous clays. These palynological trends are interpreted as shifts in depositional environment from a meandering river to a swampier/lacustrine setting across the carbonaceous clays – lignite boundary.

Seismic attribute analysis of the three trial seismic lines showed that continuity of cosine of instantaneous phase, rate of change of instantaneous frequency and amplitude of reflection strength, could be used to successfully segregate major lithological sequences of the East and West trenches through examining 2D attribute profiles and their intra-sequence lateral changes. Finer discrimination of attribute sequences using vertical attribute 'logs' at borehole locations on the East and West seismic sections proved a direct correlation between changes in attributes and the boundary between lignites and carbonaceous clay.

Comparison of palynology results and the geological and geophysical data of the East and West trenches revealed them to be environmentally distinct from one another. The West trench area is interpreted as belonging to the main palaeovalley system, and the East trench area as a tributary or bisection of the main palaeovalley.

The correlation of results obtained in this project have shown that within the late Eocene sediments of the Narnoo palaeovalley, changes in seismic attributes can be used to infer stratigraphic and palynological changes.

Minzhan Li, Curtin University: 'Using S-P time methods to accurately locate some southwest Australian earthquakes'.

The uncertainty of earthquakes' location within Western Australia is high. The uncertainty of location is originating from the poor seismic networks, quality of recorded data reading, and velocity model. There are many methods that have been tried to improve the precision of earthquake location, but the uncertainty of locations of events is still high in south west Australia. Yilgarn Craton is considered seismically active area. It is believed that the majority of events happened in this area have cluster nature with shallow depth (<5 km).

In this study, the manually s-p time method was used on clustered events in South West Australia zone, including Kellerberrin, Kalannie and Koorda area. Because the data recorded at more closed temporary stations are used, the corresponding results should have better quality. The cluster centers are improved in each swarm. One of them is same as the cluster center suggested by Dent (Koorda, 2011).

The s-p time at close stations and similar seismograms of events within same cluster indicate these events are much more closely located than Geoscience Australia suggested. The locations of events have been improved in this study. Compared to IASPEI model, WA2 model is more suitable in SWA zone. It is necessary to work more on velocity model to improve the accuracy of location of events.

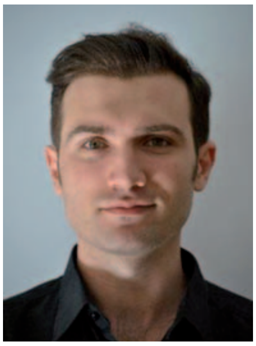
Shihao Chen, Curtin University: 'Seismic Processing of high resolution long offset 2D data over a large displacement fault: Perth Basin WA'.

Curtin Department of Exploration Geophysics in partnership with the Western Australia Department of Water have acquired and processed new geophysical data spanning 2000 km^2 of the Perth Basin for better understanding the geological structures that have significant impact in process of design hydrological model and optimal water exploitation regime. The main goal of the reprocessing the seismic line, acquired along the Bindiar road, was to explore and carefully parametrize each processing step in order to improve quality at each stage for the purpose of better imaging of the Badamina fault. Even smallest improvement, i.e. in pre-processing phase, will have a significant impact on the next coming processing phase. Also, different strategies were used for the defining the near surface velocity model, such as including the variable weathering velocity along the line (usually, processors are using only one the most representative value). In order to improve static corrections, various offset ranges were tested. Significant period of time was devoted to pre-processing phase, where several methods were used for coherent noise removal (surface waves, direct and refracted waves and their repetitive pattern due to bouncing energy between fresh rock and surface, which significantly masks near surface events of interest). Thanks to detailed tests and pre-processing modules parametrization, we managed to remove the all types of coherent noise form the data. Thanks to previous steps, velocity analysis was more reliable, as well as quality of residual static correction calculation. Additional improvements of the velocity model were done through DMO processing. Obtained DMO velocity model used for CRS processing gave satisfactory result that was adopted as a final product. Migrated CRS stack, after depth conversion, revealed area of interest in much better details with improved spatial and temporal resolution, confirming the results of other geophysical methods used, such as TEM, ERI, as well as the results from boreholes in the vicinity of the seismic line.

Sheng Han, Curtin University: 'Kinematic redatuming using emergent rays'.

Redatuming aims to recover the seismic events distorted by irregular topography and complex weathering layers. This correction normally is conducted by placing source and receiver to a new imaginary surface below the complex overburden, and it is conventionally conducted by static correction or wave-equation based redatuming methods. However, while the former method has fast computing time, it assumes seismic waves only travel vertically in the overburden; the latter method produces more accurate results, but costs a huge computing time. This project presents a method that is slotted in between these two extrema. The presented method involves using horizontal slowness for the same emergent ray to assign the given sample the new source and receiver position on the new datum, and then subtract the one way travel time from acquisition surface to new datum. The method can be used for anisotropic or heterogeneous media. It can give comparatively good results as compared to the finite difference redatuming method on the synthetic models that are tested in this project, and it can be further developed using velocity independent scheme to become a method that does not require a known velocity model.

Ryan M. Vitas, Curtin University: 'Pre-stack depth migration of the Balaka 2d seismic line'.



This paper presents an insight into pre-stack depth migration of seismic data acquired near Broken Hill in NSW, Australia. The survey in question, known as the Balaka seismic line, was designed and implemented as part of a large scale hydrogeological investigation into drought security for the region. The seismic line was carried out as a means of delineating structural features that were imaged using airborne electromagnetics.

With today's availability of cheap processing power, modern practice strives to conduct seismic imaging as accurately as possible. It has already been well established that the pre-stack depth migration algorithm is the most robust and effective migration technique for imaging the subsurface. Where this imaging technique has been rapidly growing in popularity since the influx of these fast, modern processing systems.

The focus of this project is to analyse a number of necessary techniques required to go from raw seismic data to a full depth migrated image, while simultaneously looking at different migration methods. The primary migration algorithm involved will be the Kirchhoff integral method, and the dissertation itself is sub-divided into four main chapters: 1) introduction; 2) time processing; 3) time imaging; 4) depth imaging; 5) concluding remarks.

Pre-stack depth migration is already accepted as the most complete and accurate migration method, and the findings of this project support this conclusion. The final pre-stack depth migrated image was able to not only increase the lateral continuity and resolution far better than the other techniques, it was also able to illuminate a secondary potential lithological boundary at depth which may be of interest in regards to interpretation.

The results of this final depth image will be able to be used in assisting further interpretations made for the Broken Hill Managed Aquifer Recharge project. These include gaining a greater insight into the geological structure of the subsurface, and even assisting in constraining any necessary future geophysical surveys.

Layne van Zaanen, Curtin University: ‘Comparison of borehole seismic receivers’.

Jefferson Bustamante, University of Western Australia: ‘Modeling Stress-Induced Azimuthal Anisotropy’.

New discoveries of hydrocarbon reservoirs are getting deeper and in increasingly complex geology, as a consequence one commonly needs to re-evaluate the isotropic acoustic assumption when trying to improve the precision of the analysis. One way to lessen this assumption is to evaluate elastic materials under anisotropic conditions. The aim of this thesis is to evaluate which rock physics model, the one presented by Mavko in 1995 or the model proposed by Sayers in 2001, generates the best theoretical predictions. A comparative analysis between the two models is presented. Theoretical descriptions of the approaches and applications are evaluated. The models are then compared for three different kinds of rocks: Massillon sandstone, Barre Granite, and Ottawa sand. Finally, a 3D finite-difference model is used to evaluate how the models could be used in further analysis. It is found that in general, Mavko’s model generates better approximations with a maximum calculated error of 4% on the Massillon sandstone. It is also found that neither of the models is a good approach when comparing with unconsolidated rocks.

Environmental geophysics

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Using drones to create base maps

Welcome readers to this issue's column on geophysics applied to the environment. In this issue we are looking at a subject that gets a lot of press these days: unmanned aerial vehicles, better known as UAVs or drones. I won't be showing anything revolutionary here – pretty much run-of-the-mill use of a drone's camera to make a base map. Nevertheless I was impressed, it took less than two hours to fly and some time to process, but the product was impressive and would have taken much more time and money without the drone (not to mention an aeroplane).

Anyway, one day in late winter this year my friend Justin Payne (geology lecturer at University of South Australia) called me to say that he needed 'help' (mostly he was showing off his work toys) making a base map and 3D model of a beach near Adelaide that he wanted to use as a mapping project for a first year class that he was teaching. So we went to this great exposure on a beach south of Adelaide (the beach in the rocks just to the north of the 'north bay' part of Carrickalinga if anyone knows the area).

The UAV that we used was a DJI Inspire (here is the base model website: http://www.dji.com/inspire-1), which according to Justin is one of the best medium-sized, ready-to-fly drones available for the professional market, and is often used by videographers. It's a battery-powered quad copter, with an approximately 15 minute flight time (we had four spare batteries for our project). And it can cruise along at up to 80 km/h. To make the map and 3-D model Justin used a commercially available software package called Pix4D (there are some nice mining related videos and fly-through models on their website https://pix4d.com/industry/mining/). To vastly oversimplify, this type of software takes all of the captured photos (and their GPS locations) and searches for common points within the photos. It then creates a point cloud based on the 3D position of each common point as determined from the different viewing angles (ray paths) of each photo that has the identified point. The point density from this starting grid is increased (probably splined) to produce a much denser point cloud which forms a pseudo-surface of closely spaced points. This dense cloud then has a mesh overlain over it that then is coloured either as a DEM or drapes the photos of the area over the model to make the photo-realistic model.

So, on to our project. Figure 1 shows the field area (the rocky beach below us), with Justin and me flying the UAV (Justin was the pilot, I was the camera operator – at least I got my own console). Justin would hover the UAV at a location, I would snap the shutter on the camera to get a straight-down shot of part of the area, and he would move on. Figure 2 shows Justin landing the UAV.

For this area, approximately 40 m × 150 m, we took something like 125 pictures at a nominal elevation of 30 m. We spent about an hour 'in the field'. Justin spent about another hour processing the data. Figure 3 shows the locations of the photos that we shot on the day and the path that the drone took. Figure 4 is the photo-realist model of the area. Justin used a subset of the whole area for his class, specifically the nice rock exposure in the lower right with the fold features showing on the surface. The 3D model has around a million faces with just over half a million vertices and can be explored here: https://skfb.ly/VTYr (press Ctrl and, left and right click to zoom in and out if you don't have a scroll wheel).

I'm sure that many of you already know about this type of application of UAV technology; to me it's new, and I was mostly impressed with the relative ease of making a high quality base map of an area. There are lots of companies out there that make the hardware as well as the software and people are working on new payloads for UAVs all the time. I'm aware of a few geophysicists who are working on systems to collect data (not just take photos) using UAVs and will see if I can't convince one or two of them to divulge some of their secrets over the next few months.

Figure 1. *Justin and me hard at work. The field area is that rocky beach below us.*

Figure 2. *Justin landing the chopper to change the batteries.*

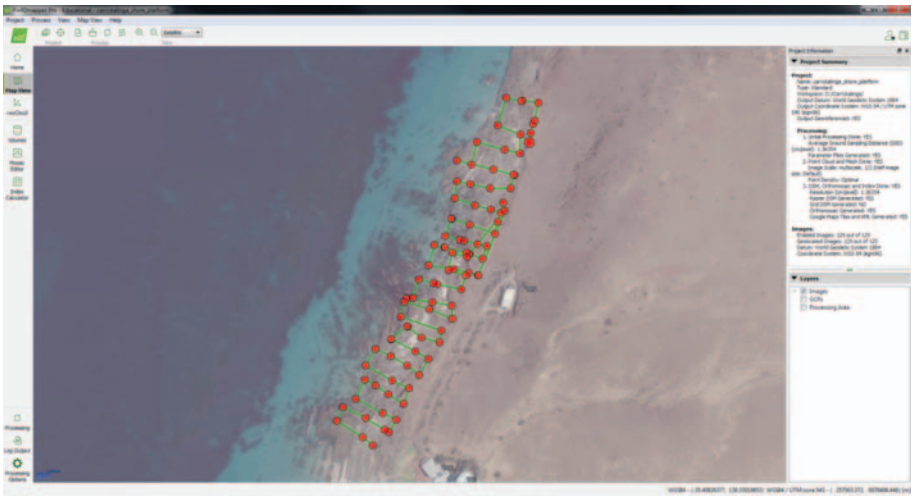

Figure 3. *Screen grab from the processing program showing locations of source images.*

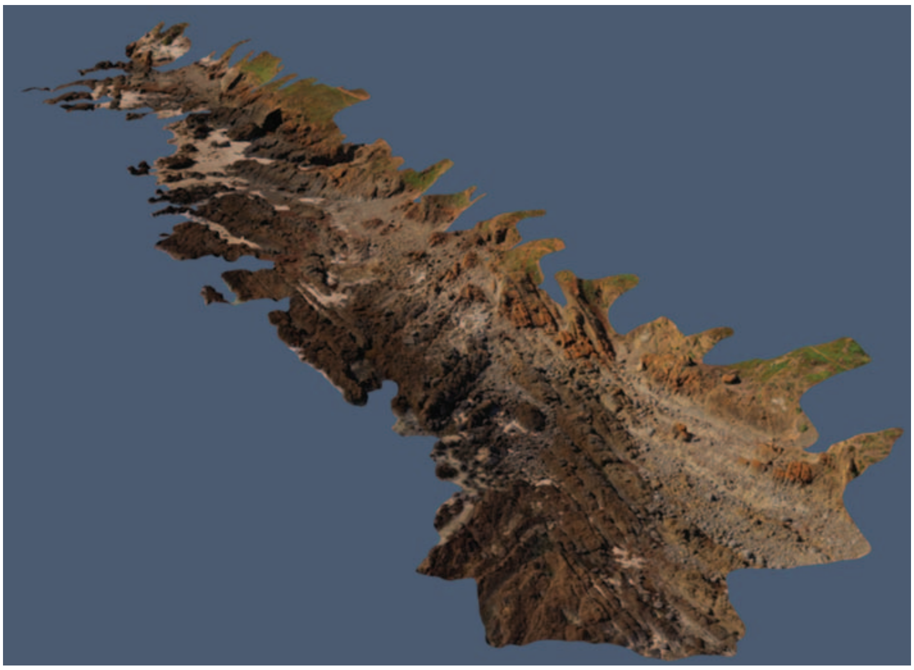

Figure 4. *Screen grab of final 'photorealist' model.*

Minerals geophysics

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Conference workshops: do they work for you?

Workshops are an integral part of our ASEG Conferences, and I try to attend at least one at each conference. This year it was 'IP Processing and QC – from amps in the ground to an Inversion input' convened and organised by Kim Frankcombe, in part at least a follow on to Steve Collins' 2015 Perth Conference workshop 'Modern 3D-IP surveying. Practical techniques and short cuts – benefits, limitations and pitfalls'.

It set me thinking about the role that these workshops play, what makes a successful workshop, and how to get the most out of them.

Workshops styles might be considered to be in one of two formats – tuition or interaction. Kim's workshop definitely fell in the latter category. Tuition style workshops clearly have education as their prime purpose. They can be as general as 'Geophysics for geologists' or as specific as a software training course. While interaction is not discouraged, the prime purpose of this style of workshop is the imparting of knowledge, usually by personnel experienced in the topic. I have found software-specific workshops to be more effective if the participants have had some prior exposure to the software in question – less time is spent coming to terms with terminology and basic processes, so more time can be devoted to finding out just what the software really can do for the participants.

With interaction workshops, education is again the aim, but the process is somewhat different. Rather than principally a teaching exercise, interaction between presenters and participants, and often between presenters themselves, is encouraged. Participants with practical experience in the workshop topic benefit particularly from these exchanges.

mineral exploration geophysics is by no means an exact science where a formulaic approach can be taken. There's often more than one pathway, so there's scope for individuality, intuition, flair, experience

The workshop format adopted by Kim was well-suited for interaction. In the morning session, four industry practitioners who had processed the same data set (of unknown provenance) to a final 3D inversion model prior to the workshop, explained their processing routines and presented their results. The four 3D inversion models generated were then assessed by an experienced independent arbiter (Bob Smith). In the afternoon session, invited individuals, mainly from commercial geophysical contracting organisations, elaborated on their individual approaches to data collection, processing and presentation. In some cases, not unexpectedly, this tended to become a sales pitch.

Interestingly, despite the somewhat different approaches, all four participants in the 3D inversion exercise produced broadly similar models, although there were differences in detail. I found this heartening – mineral exploration geophysics is by no means an exact science where a formulaic approach can be taken. There's often more than one pathway, so there's scope for individuality, intuition, flair, experience, etc. For example, one divergence of opinion that emerged from the workshop was the role that 2D inversion played as an intermediate step in the 3D inversion process. Opinions differed – some felt that 2D inversions were essential, and others by-passed them completely. This, in turn, led to differing approaches to survey design. For practitioners, exposure to the different approaches taken can be very beneficial.

Was this a good approach for an interaction workshop? I think it was – a good blend of participation and education, and stimulating to boot.

And my thoughts on workshops at our Conferences? To my mind they are a valuable component of the industry education and communication process, and should definitely be fostered. Person to person interaction is a great way to impart knowledge and exchange ideas. The tuition style workshops fulfil specific education needs; the interaction style workshops provide an ideal forum and encourage dialogue between industry practitioners. And our Conferences provide a purpose built opportunity, sometimes the only opportunity, to get presenters and participants together.

What do you think?

Seismic window

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The age of multi-client seismic

Under the Australian work programme bidding system, seismic data (and well completion reports) become ‘open file’ after 2–3 years. This means that seismic surveys are available to anyone and, as a result of this openness, the exploration industry has benefitted. Established companies and new entrants have been able to compile regional databases to help develop ideas and concepts. This is an excellent system but it’s not all perfect. Often the most recent or best version of the processed data is not submitted. I recall a story from long ago when seismic lines were plotted on films, before the requirement to submit digital versions of the data, one company would provide films that were produced slightly out of focus so that competitors didn’t get too much advantage.

The open file system applies to data acquired by exploration companies by virtue of permits awarded under the work programme bidding system. There is another system. The multi-client seismic model. Under this system seismic surveys are acquired by seismic acquisition companies over large areas that may straddle several permits and open acreage. These surveys were originally called ‘speculative’ surveys because they were acquired by acquisition companies over areas they thought would be popular with buyers and were recorded without much pre-commitment to buy any data. Early ‘spec’ surveys had the same rules as all other data and became open file after a few years but this was not economically attractive and successful lobbying led to more attractive terms. Nowadays seismic companies require some degree of underwriting before they commence recording and the legislation has been changed to allow the data to be owned exclusively by the acquisition company for 15 years so they can recoup their costs (and make an honest living).

Is this fair and equitable? Exploration companies pay full price for a survey on their acreage and have to make it publically available three years later, but a multi-client survey over the same area is held for 15 years while the ‘owner’ sells it to interested parties for a fraction of the acquisition cost. Perhaps the permit holders should acquire their data using the multi-client model so they too can recoup the costs by selling copies to interested parties rather than giving it away after three years.

Exploration companies pay full price for a survey on their acreage and have to make it publically available three years later, but a multi-client survey over the same area is held for 15 years while the ‘owner’ sells it to interested parties

Disadvantages of multi-client surveys include the complicated licensing fees and uplifts that at times require a degree in cryptography to understand, and the lack of control over acquisition and processing parameters that is often frustrating to interpreters. But the multi-client model is not all bad. For instance, as areas become more mature and permit sizes shrink the multi-client surveys are more efficient than proprietary surveys and cost less per square kilometre to acquire. And a large multi-client 3D survey can give insights into the regional geology that are not possible with a patchwork of small surveys of varying age and quality. In addition, there is sometimes an accompanying interpretation report or set of key seismic horizons produced by the vendor as either a separate product or part of the overall package.

There are many examples where multi-client data has helped the Australian industry – for instance the Onnia 3D in the Vulcan sub-basin and Panneus 3D in the Carnarvon Basin are still being used decades after the initial acquisition. More recently, the Capriolus 3D was used successfully to aid in the Phoenix South-2 and Roc-1 & 2 discoveries. Looking back, perhaps these wells would not have been drilled if only open file 2D seismic was available or the permit holders had to fully fund a large 3D seismic survey.

Webwaves

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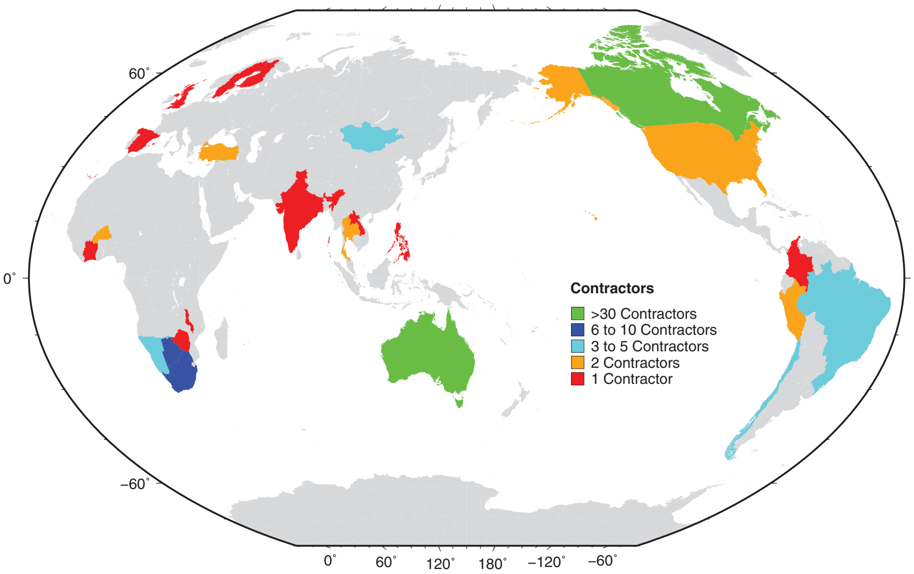

Figure 1. *Worldwide distribution of contractors listed in the ASEG's contractor database. The map is dominated by Australia and Canada, and 12 countries have single entries.*

The new ASEG website: continuing developments

Much of the Web Committee's efforts in recent months have been directed towards ensuring that the website's transition between content management systems has been as smooth as possible. A necessary part of that transition has been a bias towards incremental improvement rather than revolutionary change. For the most part we have succeeded, despite the odd regrettable incident where Members were unable to access journals. Evidence that the new site is functioning well may be found in the way that the SA/NT Branch's recently closed Annual Wine offer has proceeded.

Members will have noticed small sections in previous issues of *Preview* with brief descriptions of historical geophysical surveying equipment. These were drawn from an article by John Stanley (this issue) and are slowly making their way online as exhibits in a virtual museum. The equipment museum is at https://www.aseg.org.au/equipment-museum.

Another addition to the web site has been proceedings of a workshop held as part of the 25th ASEG Conference in Adelaide. Jayson Meyers and Chris Wijns have arranged for presentations made during the workshop on 'Near surface passive seismic surveying for mineral exploration, environmental and engineering applications' to be uploaded. All 13 presentations are in PDF format and available to download at https://www.aseg.org.au/workshop-proceedings. We welcome enquiries by other workshop conveners who are interested in reaching a wider audience.

The main efforts of the Web Committee for the next few months will be focussed on updating the Contractors database (https://www.aseg.org.au/employment/contractor-database). Originally compiled by Ken Witherly and Pat Killeen, this database currently holds contact details of 118 contractors, and is designed to facilitate the search for geophysical contractors in different parts of the world. Figure 1 plots the distribution of contractors throughout the world. Twenty-five countries are represented. Reflecting the database' origin, Australia (39) and Canada (31) have the most entries. Seven contractors list countries in Africa as their location, and five contractors list Asian countries as their location. One of the Web Committee, Ian James (Terraspect), will be leading efforts to add details such as methods and country of operation to existing entries. This information will enable searches to be much more efficient. With this in mind, we urge all contractors to consider the information in the database, and how much more they can provide to allow their services to be found more easily.

The main efforts of the Web Committee for the next few months will be focussed on updating the Contractors database

Data trends

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Hadoop-de-do

There have been some real game changers that have hit the ground in the last few years. Big Data Analytics, Watson from IBM, IoT and Hadoop are among these. I hear that pockets of the industry are starting to adopt some of this technology, but it still feels like we are a little behind the times.

If there is one thing that the oil industry has it is a lot of data, and most of the technology that I have listed would be easy to adapt to our needs. As an industry we also tend to only use a small portion of our data, after we weed out what conventionally has been considered surplus to requirements – but nice to have. In fact, it has always appeared to me that in seismic in particular we start with very large files and then go about reducing the size of those files as quickly as possible in order to make the data more manageable. The decision to make the data more manageable - instead of better quality, or smaller - instead of more insightful, seems odd to me, especially now that tools like Hadoop have changed the imperative to reduce the size of datasets. What I think this means is that we have some great and ground breaking options available to us – especially if we take a step back and think about our new options.

So what is Hadoop?

Hadoop is an open source programing framework that allows users to process and store extremely large datasets (large files or large volumes of files) in any environment. Imagine having a 50 Tb file you need to process but your computer only has a 2 Tb hard disk. In conventional processing you would either get a bigger hard disk (not always cost effective or even possible), or process the file in small parts, one at a time until you are able to process all of the data and gather the smaller more manageable version to move forward.

In seismic we tend to process the data in parts and then go about distilling it down to smaller packages to make it more manageable. In my view we carry out the 'distilling' process more to make the dataset smaller and more manageable than because the data we are getting rid of is not useful. For me this means that we make scientific decisions further down the track, without the full benefit of all of the data that could have been used. With Hadoop a user can store and process the entire dataset and interact with the entire file all at once. No need to distil it at all. It means we can now work in broad generalities, while at the same time retaining full access to all of the data – even if we are not using it. If we see something interesting while working we can go back and change our sample size, or dig deeper from surrounding data to confirm results that previously would have meant going back and processing the data again from scratch, which typically would be cost prohibitive.

Hadoop is an open source programing framework that allows users to process and store extremely large datasets in any environment

Why is Hadoop important?

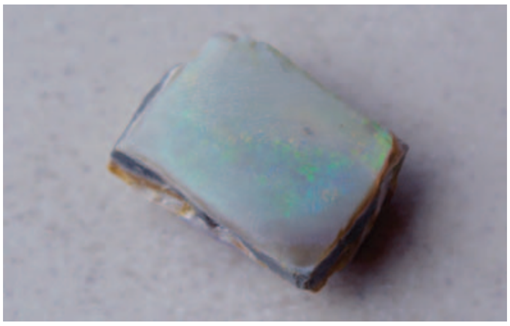
For me Hadoop is important in the oil and gas space because it allows deep diving into data, and the ability to change tack, refine, review, validate and, in the end, derive the best possible results and make the best possible decisions. It allows previously cost or time prohibitive transactions in data analysis and processing to be undertaken in an inexpensive and interactive way.
You really don't need to make the types of decisions we now make up front in data processing – made only to get the data down to a manageable size to move the project forward. If you combine Hadoop and Cloud storage you get such a scalable and cost effective work environment that more data becomes a better way to work, and teams don't need to be pressured into reducing their footprint on the network. No one needs to be in a rush to pick the attributes they feel are important up front, and teams can go back to all available data to validate things as they move forward. Almost infinite storage, massive processing power and the ability to address huge files or datasets all at once has not been possible until the last few years in any cost effective way. I don't think that as an industry we have woken up to this fact yet.

Imagine a world….

Imagine a world where newly acquired exploration data starts off life in in the cloud. No tapes to read or transport, and no need to break up datasets into pieces that fit our storage media. Navigation, positional data and support materials stored permanently in a raw form in a state that is always available to users – never offline, never on storage media that you cannot read and, since it is all online at once, always in the most modern format available (it can be converted on the fly as standards change or as new datums are derived etc.).

Imagine that we find in our geophysical community a certain thing or indicator in data that if used on any dataset gave you confidence about some geophysical property that in turn gave you exploration certainty about targeting resources. Imagine then if you could apply that knowledge to all data, on all prospects, globally, in one place, at a very low cost with the click of a button.

Hadoop, cloud storage and processing, analytics, and big data make all of this possible. All we need to do now is make it happen.



Andamooka S.A. common opal.

Don Emerson
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Opal: the queen of gems

Introduction

In this article the writer continues a quite subjective and idiosyncratic ramble through the mineral kingdom's garden of gem showpieces (Editor's note: See *Preview* 173 and 179 for other articles by Don Emerson in this vein).

For the novelist and psychopharmacological guru Aldous Huxley (1956), gemstones were the manifestation of a heightened mystical experience promising an environment:

> *of curved reflections, of softly lustrous glazes, of sleek and smooth surfaces. In a word, the beauty transports the beholder, because it reminds him, obscurely or explicitly, of the preternatural lights and colour of the Other World.*

And none more so than the opal, the subject of this article. Over the ages gem opal has always been desired for jewellery and, as the queen of gems, regarded as an eminently collectible stone.

Silica, $Si0_2$, is the second most common material in the earth's crust, after the feldspars. There are several varieties in the silica group. The six types of interest to earth scientists and collectors are quartz, chalcedony, cristobalite, tridymite, lechatelierite, and opal (Table 1). Natural hydrous silica, loosely known as opaline

Table 1. Six silicas

	Quartz SiO_2	Chalcedony	Cristobalite	Tridymite	Lechatelierite	Opal $SiO_2.nH_2O$
Crystal system	Trigonal		Tetragonal	Orthorhombic	Amorphous glass	Amorphous mineraloid,
Type	Crystal quartz, accessory mineral, ubiquitous occurrence	Cryptocrystalline quartz, fibrous or granular, widespread occurrence	Precipitated from hot fluids in cavities in volcanics, widespread occurrence in minor amounts		Fulgurite, lightning strikes on silica sand, rare	Weathered zones, volcanics, sediments, in cracks, cavities, nodules; and in marine seds., widespread occurrence
Density (g/cc)	2.65	2.60±	2.33	2.26	2.20	2.10±
RI	~1.55	~1.53	~1.48	~1.47	~1.46	~1.45
Hardness on Moh's scale	7	<7	<7	7	6±	6±
Void space	No water accessible porosity but can contain occluded fluid filled micro pores	Minor, microscopic	Minor, when in disordered form		Nil	Significant, interstitial to silica spheroid packs, but infilled and not accessible by external water

- The key optical property RI, the refractive index, is the ratio between velocities of light in air and in the mineral
- Note the decrease in density, RI, and hardness left to right in this table
- Chalcedony includes the microfibrous silicas: agate, chrysoprase, sard; the microgranular silicas (flint, chert, jasper) are more compact and tougher
- Opaline silica is a general term used when there is insufficient X-ray et al information to categorise material as opal-CT (disordered cristobalite and tridymite) in volcanic opal or opal-A (highly disordered virtually amorphous) in sedimentary opal
- In diatomaceous and radiolarian marine muds the biogenic silica in the organism alters diagenetically: siliceous ooze/opal-A-> porcellanite/opal-CT-> chalcedony/chert.
- Precious opal has a play of colours from close packed arrays of translucent silica spheres (~0.25 μ), the play of colours depends on the silica sphere size and uniformity and on random discontinuities
- Precious opal is a fragile, brittle material; the gem form of quartz, rock crystal, is tougher and more stable, and less valuable.
- Hydrothermal volcanic opal usually is more transparent than sedimentary basin opal which tends to be opaque or translucent
- In the writer's view and experience, low density opaline silica occurs frequently in several geological environments, certainly more so than is usually recognised.

Sources: Anderson and Jobbins, 1990; Deer et al., 1992; GIA, 1995; Gübelin and Koivula, 2004; Kerr, 1977; Schumann, 2006.

silica, $SiO_2.nH_2O$, occurs widely. It is a recognised regolith category in the highly weathered regions of Australia (Eggleton, 2001), and elsewhere. Opal is hydrous and not as hard and dense as other silicas. Under special conditions it can acquire unrivalled brilliance with vibrant colour flashes manifesting a splendid play of colour (POC) that changes with aspect. The colour structure, though variable, is distinguished from all imitations by iridescence from 'flat planes with striated satiny finish that are the glory of true precious opals' (Anderson and Jobbins, 1990).

The famous opal deposits at Lightning Ridge and White Cliffs in New South Wales, Andamooka and Coober Pedy in South Australia, and the spread of occurrences in Queensland, contain considerable resources of gemmy opal. The host rocks are of sedimentary origin. The small mine and individual miners of the Australian opal industry produce material valued, in the rough state, at about $70 000 000, annually.

The opal occupies an important place in the Aboriginal legends of central Queensland. In the young world of the Dreamtime a giant celestial opal dictated tribal laws and punishments. The details of this elaborate myth have been explained by Melva Roberts (Roberts, 1975). The birth of the Australian opal has been depicted in a painting by Ainslie Roberts (Figure 1).

The writer will not attempt to summarise the considerable information in numerous books and papers devoted to Australian opal and the fields in which they occur. Smallwood (2014) provides an excellent scientific discussion. For a good overview of commercial opal types and value factors see the Opal Down Under website. The aim of this article is to present some historical and background information on a beautiful, desirable and fascinating gem material, and to investigate, in a limited way, some of its lesser known physical properties and their relevance, if any, to exploration geophysics.

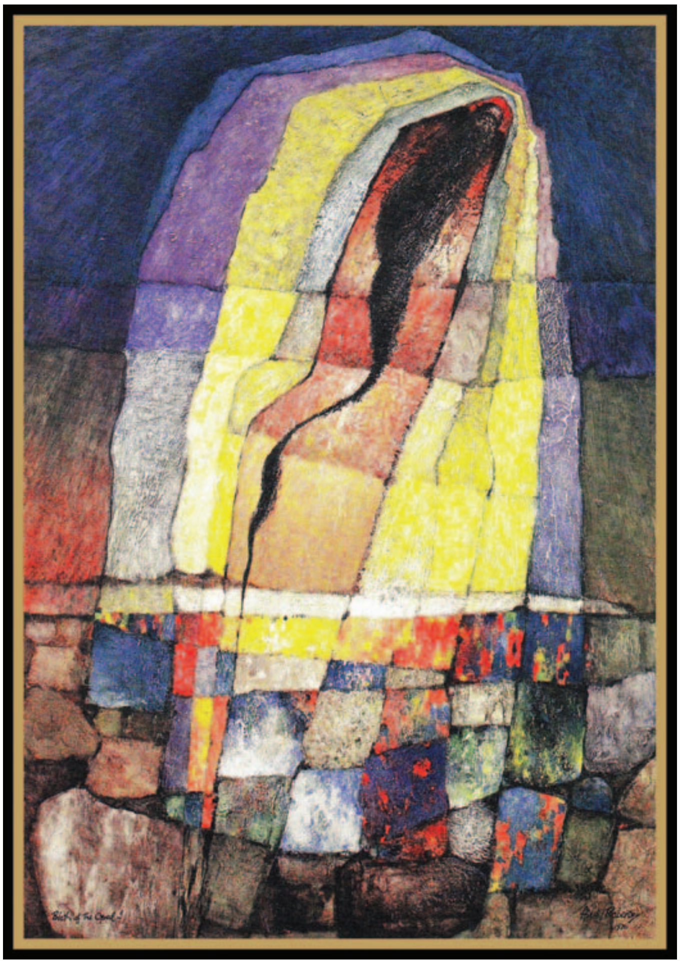

Figure 1. *Ainslie Roberts' painting of the Birth of the Opal. This acclaimed artwork evokes the formation of a marvellous material in the fractured beauty and the harshness of central Queensland. Source: Ainslie Roberts, Birth of the Opal (1975), acrylic on board © Ainslie Roberts/Licensed by Viscopy, 2016.*

Opal's occurrence

Opal is deposited at low temperatures from silica-bearing groundwater. It breaks white light into its spectral colours owing to its unusual porous mineral gel structure, comprising amorphous silica, voids, and water. In its precious form, regularly stacked, submicroscopic (.14–.30 μ diam) silica spheres of uniform size form a 3D diffraction grating with the adjacent voids which contain silica jelly cement and water. It is this arrangement of spheres and voids and the changes in refractive index at their interfaces that give the interference and dispersion, of incident white light, so pleasing to the eye (Sanders, 1964, 1968). Smaller spheres diffract the blue end of the spectrum; larger spheres, the red. In precious opal the spheres are stacked in the stable face centred cubic array. The porosity of the interstitial space, for equal diameter spheres, is 25.95%. Common opal (potch, opalite) is material consisting of irregularly sized and spaced spheres and voids that do scatter light, but only give a milky, opaque effect (Perry, 1984), but sometimes with an attractive impurity generated colouration. Distinctive or unique character is imparted to an opal by random internal discontinuities, such as sphere stacking defects and micro faults, and inclusions or patches of materials such as potch or sand. These features modify the colour generation. A flat opal surface limits the POC owing to total internal reflection of some wavelengths. Hence the use of convex surfaces or the covering of opal with a dome of material of similar refractive index.

A characteristic of opal is its water content. Opal contains 10% +/- H_2O (by weight, more by volume). This water could be in the form of both bound and molecular water. Pore wall silica has sufficient negative charge to ionise water in contact with it to form bound surface hydroxyls. Molecular water includes water in silica cages, in occluded voids between the spheres, in capillaries, and as inclusions in opal itself. It is *not* free draining water such as may occur in a porous, permeable sandstone. Opals are virtually impermeable in the absence of fractures (which would flaw the material anyway).

Precious iridescent opal includes: white opal, which has a light basic colour, black opal with a dark basic colour, boulder opal, which is precious opal on, or as seams in, a host rock (e.g. ironstone), and matrix ('pinfire') opal with precious opal disseminated in a host rock. The beauty of boulder and matrix opal is enhanced by the drabness of the host. Common opal, which lacks POC, includes agate opal with light and dark opal layers, porcelain opal with an opaque white milkiness, fire opal with a milky orange colour, and several other varieties (Sutherland & Webb, 2000; Schumann, 2006). Opals with a dark underlying colour are more valuable than those with a light background as the darker stones tend to a more vibrant colour display. Australian black opal is highly prized; a quality stone may fetch $15 000 per carat ($75 000 per gram) – serious money.

Figure 2 illustrates black opal, white opal, boulder opal, and common opal. Figure 3 shows two Australian opals set in gold rings.

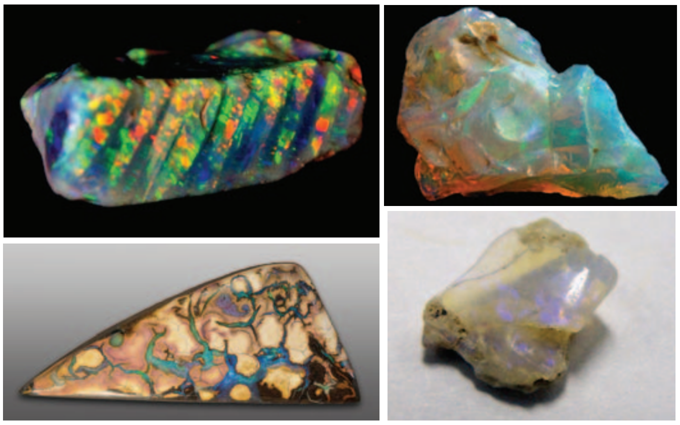

Figure 2. *Four of the main types of opals: top left – black, top right – white (light precious), bottom left – boulder (opal in ironstone), bottom right – opalite (common opal). The depicted opals each weigh ~60 carats i.e. ~12 grams; their volumes are small (~6cc). In opalised sedimentary strata, or in volcanics, opalisation may be widespread, but the opal material occurs in concentrations as small pockets or nodules, or as thin erratic seams; the opal is a minor constituent of the host lithology. Sources: top left – 'The Dream' kingstone of black opal rough parcel (cropped) by Danmekis/CC BY-SA 3.0 https://commons.wikimedia.org/wiki/File:58.05ct_Lambina_Black_Opal_Rough.JPG, top right – photo by Lech Darski/CC BY-SA 3.0 https://commons.wikimedia.org/wiki/File:Opal_Welo_-Welo,_Afar_Province,_Etiopia,_Afryka.jpg, bottom left – photo by Hannes Grobe/CC BY-SA-2.5 https://commons.wikimedia.org/wiki/File:Opal-f_hg.jpg, bottom right – photo by CRPeters/CC BY-SA 3.0 https://commons.wikimedia.org/wiki/File:Potch.jpg.*

Figure 3. *Opals for adornment. These fine Australian opals, photographed on ferruginous sandstone, have been set in gold rings crafted in Australia; they belonged to Annette Emerson. Left – Queensland boulder opal, long dimension 18 mm; right – South Australian white opal, long dimension 14 mm. Photo by Lainie A Kalnins/CC BY-SA 3.0.*

Opals occur as nodules, veinlets, cavity fillings, layers, seams and encrustations. Many kinds of rocks host opal. They are found in volcanics in Australia (e.g. Tintenbar, NSW), the Americas, Africa and Europe. It is believed that deposits in Czechoslovakia-Hungary supplied the ancient world. The famous and extensive Australian deposits, discovered in the late 1800's, are different, being mainly hosted by weathered Cretaceous sediments. These are in the Surat Basin's Finch Claystone (Lightning Ridge, NSW) and in the Eromanga Basin's Bulldog Shale (Coober Pedy, SA) and Winton Formation (Winton, Qld). Opal is often hosted by or associated with 'ironstone'. Pseudomorphs of opal after fossil animal remains are found in these sedimentary deposits. Precious opal specimens are small. Usually, if three dimensional, they are in the mm-cm range; two dimensional materials, such as seams or layers, commonly are quite thin, of the order of mm.

An expanding industry has developed from the 2008 discovery of 'Welo' opal to the north of Addis Ababa, Ethiopia. Colourful opals are found in nodules formed in volcanic ash layers (Downing, 2011). These opals now compete with Australian materials in the cheaper light opal category in markets worldwide. An example is shown in Figure 2 (top right).

Table 2 indicates some differences between sedimentary and volcanic opal. Australian opals generally are denser and more responsive to long wave ultraviolet than overseas volcanic types, which also tend to have lower refractive indices.

Opal in ancient times

The Latin for opal is *opalus*, apparently derived from the Sanskrit *upala* for 'precious stone' thought to have come from India. This source was pure conjecture and seems unlikely. India probably was a code word for remote locations known only to traders. Cavity-fill opal is known to occur at several locations in eastern European volcanic regions. The Slansky Highlands' andesites, trachytes, and tuffs, in the east of present day Slovakia (formerly Hungary) supplied white opal during the 17th to 20th century period and probably much earlier. The opals came mainly from the area around the old mining town of Dubnik. So ancient opal in the Mediterranean world could have been sourced from such settings.

The author of *Naturalis Historia (NH)* Gaius Plinius Secundus (AD 23–79) was, and is still, rightly renowned for his encyclopaedic work of 37 books containing a vast number of facts, and factoids, on numerous topics, including gemstones presented in Book 37 (Bostock and Riley, 1857; Mayhoff, 1897; Eicholz, 1971). Indefatigable as ever, he died investigating the catastrophic eruption of Vesuvius. The opal of his day is described *NH* 37.80,81:

> *…. opali, smaragdis tantum cedentes … atque ut pretiosissimarum gloria compositi gemmarum maxime inenarrabilem difficultatem adferunt. est in his carbunculi tenuior ignis, est amethysti fulgens purpura, est smaragdi virens mare, cuncta pariter incredibili mixtura lucentia. alii summam fulgoris Armenio colori pigmentorum aequari credunt, alii sulpuris ardentis flammae aut ignis oleo accensi. magnitudo abellanam nucem aequat.*

> …. in value opals yield only to emeralds …. as they embody the splendour of the costliest gems they present the

Table 2. Some physical features of precious opal (after Smallwood, 2014)

Precious opal type	Density (g/cc)	Refractive index	Ultraviolet light response (LWUV, long wave UV)
Australian white, sedimentary Opal-A	≤2.15	≤1.45	Bluish white fluorescence then yellow-green phosphorescence
Overseas; white, volcanic Opal-CT	2.05±	<1.45	Usually none
Australian black, sedimentary Opal-A	≤2.15	≤1.45	Similar to Australian white opal but less intense

greatest difficulty of description. They display the delicate fire of ruby, the purple brilliance of amethyst, and the sea-green of emerald, all combined in concert with incredible brilliance. Some regard the effect of the vivid colouring as resembling azurite pigment; others the flames of burning sulphur or of a fire lit with olive oil. The size of an opal is that of a hazel nut' [the ovoid hazelnut is ~15 × 10 mm].

Pliny's extensive compilation of materials and things occasionally includes interesting anecdotes, and the opal has one of them. It concerns the turbulent times of proscription in Rome in 43–42BC when hundreds were outlawed and their goods confiscated by the triumvirs Mark Antony, Octavian (later Caesar Augustus), and Lepidus. It seems that Mark Antony liked opals *NH* 37.81,82:

> *insignit etiam apud nos historia, siquidem exstat hodieque huius generis gemma, propter quam ab Antonio proscriptus est Nonius senator …. ille proscriptus fugiens hunc e fortunis omnibus anulum abstulit secum. certum est sestertio vicies tum aestimatum, sed mira Antoni feritas atque luxuria propter gemmam proscribentis, nec minus Noni contumacia proscriptionem suam amantis, cum etiam ferae abrosa parte corporis, propter quam periclitari se sciant, et relicta redimere se credantur.*

> also there is for us a noteworthy story in that there is in existence a precious opal (ring) for which the senator Nonius was outlawed … This Nonius, proscribed and fleeing, took away with him, out of all his wealth, this ring alone. There is no doubt that the ring was then valued at 2 000 000 sesterces. What is more remarkable is the brutality and immorality of Antony invoking proscription because of a gemstone, and the obstinacy of Nonius in refusing to part with the reason for his outlawry. For even wild creatures are believed to save themselves by gnawing off the body part, which they would know imperils them, leaving it behind (for the hunter).

An explanation of the allusion can be found in the Aesopian fable, The Beaver, *Fiber*, a frequently hunted wild creature. Phaedrus (*c.*15BC–*c.*AD50) is believed to have written this (Perry, 1965):

> *Canes effugere cum iam non possit fiber*
> …
> *abripere morsu fertur testiculos sibi,*
> *quia propter illos sentiat sese peti.*
> *divina quod ratione fieri non negem;*
> *venator namque simul invenit remedium,*
> *omittit ipsum persequi et revocat canes.*
> *Hoc si praestare possent homines, ut suo*
> *vellent carere, tuti posthac viverent.*

> When the beaver cannot escape the dogs … they say he gnaws off his gonads because he knows that it is for them he is pursued. I cannot deny that this happens by sacrificial foresight, for the hunter, as soon as he has found the raw material for his potions, disregards the beaver and calls back his dogs. If men could take it on themselves to forfeit their property they would live safe into the future.

Actually the beaver was hunted for the pungent liquid (*castoreum*) in two sacs in his nether regions; this was used in perfumes and medicines. However, the moral of the tale is that it is better for one to lose the family jewels than one's life. Nonius really must have loved that opal. A *sestertius* then had several times the purchasing power of today's dollar. Some stone indeed.

Medieval and pre-modern opal

Marbod (1035-1123), Bishop of Rennes in Brittany, was an eminent literary figure in his day. He was devoted both to the Christian and classical worlds. He wrote attractive hymns, but he and the finest minds of his contemporaries were especially enchanted by the emblematic signs regarded then as hidden in nature, and especially by the mystical and inexplicable powers deemed to reside in precious stones. His *Liber Lapidum* (Book of Stones) was immensely popular for centuries. Lines 633–637 *(De opthalmio;* Beckmann, 1799; *opthalmius* is a medieval corruption of *opalus*) account for opal:

> *Avertens oculis morbos ophthalmius omnes,*
> *Asseritur furum tutissimus esse patronus;*
> *Nam se gestanti visus conservat acutos,*
> *At circumstantes obducta nube retundit,*
> *Ut spoliare domos possint impune latrones.*

> Opal diverts all evils from the eyes
> It is claimed to be a very reliable protector of thieves
> For it maintains the keen vision of the opal carrier
> But clouds the sight of bystanders
> So that robbers can plunder residences with impunity

Marbod's devoting only five lines to prey-dazzling by the prettiest of gems seems curious given his effusions on others, e.g. 26 lines on lapis lazuli, 21 on pearls, 20 on lodestone, and 18 on the *alectorius* – a castrated cock's gizzard stone valued for its medical and mystical properties. Marbod, indubitably, did not want to highlight an instrument for the facilitation of sin to his eager and pious readers. Perhaps the negative aspects of opal's reputation commenced around this time.

The belief in the relationship between opal and sight continued on to the 17th century. In 1630 the English dramatist Ben Jonson (New Inn 1, 6) wrote: 'I had no medicine, sir, to go invisible; nor opal wrapped in bay leaf in my left fist, to charm their eyes with.'

In 1601 Shakespeare (Twelfth Night, 2, 4, 77) referred to opal's mutable colours in a clever metaphor delivered by the clown to Duke Orsino: 'Now, the melancholy god protect thee, and the tailor make thy doublet of changeable taffeta, for thy mind is a very opal.' Taffeta is an expensive, shimmering silk with a reflectivity that varies depending on the light and angle of view. Here, the opal indicates an excitable, changeable personality.

One of the most passionate and evocative descriptions of any gemstone was written by Petrus Arlensis (1610). He waxed eloquently on the opal, presumably a milky white precious opal from the volcanic occurrences in Hungary-Slovakia. One wonders what he would have said about high quality Australian black opal.

> *Colores varii in Opolo ad visionis oblectamentum conferre multum valent, imo ad corda & interiora alteranda efficaciam maximam praestant, & mirantium oculos summopere oblectant. Unus prae aliis ad meas pervenit*

> *manus, in quo tanta pulcritudo, decor, & venustas elucebat, ut vere lapides omnes ad se vi trahere gloriari posset, cum aspicientium corda indeflexe, & indefinenter everteret, deverteret, ac alligaret: Grossitie unius avellanae ab Aquilae aurea miro elaboratae artificio unguib(us) strictus erat, coloresque tam vividos & varios habebat, ut tota caeli pulcritudo in illo conspiceretur: Decor ex illo exibat, Majestas ex fulgore prope divino erumpebat. Radios tam claros & graves emittebat, ut aspicientibus terrorem incuterent. Quid plura? virtutes & proprietates a natura sibi insitas deferenti concedebat: nam corda aspicientium invisibili jaculo jaculabatur, oculos caecutiebat: pectora licet animosissima fortissimaque concutiebat, totum denique astantis corpus terrore replebat: ad amandum, honorandum & colendum fatali quadam coactione impellebat. Vidi, expertus, & coram Deo testificor, vere talis lapis summo & inaestimabili pretio adstimandus erat.*

> The kaleidoscope of colours in an opal conveys an abundance of delight to the eyes. I should say, more correctly, they offer a very effective means of changing one's soul and character, and also ravish the sight of astonished viewers. An exceptional specimen came into my hands. In it there was manifest a graceful comeliness and a charming quality of such intensity that it could truly take pride in all other stones trailing in its wake; it completely reorients and firmly grips the viewers' emotions inflexibly and without limit. Thick as a hazel nut, it was clasped in the claws of a golden eagle fashioned with wonderful skill, and had such lively and varied hues that the beauty of the heavens, in its entirety, was discerned. An attractiveness and a grandeur akin to celestial lightning all but issued forth from it. The flashes it released were so bright and overpowering that they instilled great fear in those beholding it. What more to say? It transferred the special properties and qualities, implanted in itself by nature, to the person carrying it around. Moreover it struck the minds of onlookers with an invisible arrow; it blurred vision; it upset even the bravest and strongest hearts; in short, it filled the whole body of the bystander with terror. It set in motion, by some kind of fatal compulsion, feelings of love, respect, and religious awe. Out of the basis of what I saw and experienced, I testify in the presence of God, truly such a stone had to be considered worth an incalculably great amount.

What more to say, indeed?

Unlucky opal

In myth and anecdote opal has been reviled as the evil eye, the stone of disaster. This does not bear examination. For example, Evans (1970) reports that Alphonso XII of Spain (1857-1885) gave an opal to his wife on his wedding-day, and her death occurred soon afterwards. Before the funeral he gave the ring to his sister, and she died a few days later. The king then presented it to his sister-in-law, who died within three months. Alphonso, astounded by these fatalities, decided to wear the ring himself, and within a very short time he, too, was dead. The Queen Regent then suspended it from the neck of the Almudena Virgin in Madrid. This act of piety halted the deadly chain of events. However, the carved Virgin was doubtless immune to the 1885 cholera epidemic that raged through Spain then, killing over 100,000 people from every level of society, and so, it seems, the four unfortunates in the royal family. All these Spaniards were unlikely to have owned a piece of opal.

In the last of his novels, Anne of Geierstein, Sir Walter Scott gratuitously and probably unintentionally damaged opal's reputation by linking it to misfortune. Apparently, his baleful tale of the character Lady Hermione contributed to a wariness if not rejection of opal among his wide readership in the dominant (British) empire of the time. Lady Hermione, of mysterious origins, wore a dazzling opal in her hair. This opal sparkled when she was happy, gleamed red when she was angry, and its radiance was quenched when sprinkled with holy water. After falling into a swoon she was carried to her chamber where, next day, just a heap of ashes remained on the bed on which she had been laid. The life of a mysterious stone (averse to holy fluid) was linked to the life of mysterious Hermione. This, published in 1829, really spooked the opal trade.

Despite the bad publicity, Queen Victoria liked opals. This helped sales of Australian material in England during the latter part of the 19th century.

Opal is relatively soft, fragile, and brittle for a gemstone. It can be difficult to fashion into jewellery. It is sensitive to heat, which causes fracturing and can result in loss of colour. Of course, miners and marketers of competing gems emphasise the negative features of its history and its physical properties. Hence its reputation as an unlucky stone.

Opal synthesis and treatment

Imitation opals were fabricated in the ancient world. Pliny (*NH*) 37.83 commented:

> *nullos magis fraus indiscreta similitudine vitro adulterat. experimentum in sole tantum, falsis enim contra radios libratis digito ac pollice unus atque idem tralucet colos in se consumptus, veri fulgor subinde variatur et modo ex hoc plus, modo ex illo spargit, fulgorque lucis in digitos funditur.*

> There is no stone more counterfeited by a fraudster than the glass imitations closely resembling opal. It can only be tested in sunlight. When fake opals are poised between thumb and finger against the sun's rays only one attenuated colour shines through. The flashing brightness of the true stone changes continually. At one moment, then another, there is more colour dispersion from different parts of the stone, and beautiful light diffuses onto the fingers.

Much later the polymath Athanasius Kircher (1678) in his *Mundus Subterraneus (MS)* discussed several glass synthetic gem-making techniques, *Opali Imitatio MS* 12.4:

> *Adulterari duplici vitro, vel colore, ut aliae gemmae Opalus non potest, Scribit tamen a Porta, calcem stanni in vitrum crystallinum excandens injectam illud obnubilare & colorare Opali instar: Sed oportet saepius ex igne eximere, & accommodare, donec quis voti compos fiat. Quercetanus a spiritu nitri alembicum vitreum intrinsecus ita tingi variis coloribus asserit, ut Opalus videatur.*

> Opal is not able to be counterfeited by coloured glass compounds as can other gems. Yet Porta writes that firing tin powder into crystal glass clouds and colours it in the manner of opal, but it ought often be removed from the fire

and the procedure adjusted until such time as one's expectations are realised. Quercetanus claims that alkaline solution stains the inside of a glass still (alembic) with a variety of colours resembling opal.

It seems that the ancient technique of imitating opal with glass, as mentioned by Pliny, did not survive into the alchemy of Kircher's time.

Attractive manufactured opals, with similar chemistry and structure to natural opal, have been available since 1974 (Anderson and Jobbins, 1990). The Pierre Gilson process involves synthesis by chemical precipitation of silica under hydrostatic pressure. These opals have only slight differences in hardness (lower) and density (lower) when compared to true opal. They may be recognised by their mosaic patterns of colour inside which scaly or 'lizard skin' textures and columnar structures can occur.

Good looking plastic opals are also manufactured, from styrene spheres, but handling them gives an immediate clue to their origin as they are soft and very light in weight with densities approaching 1.0 g/cc.

Opal is often treated with smoke, dye, oil, wax, plastic, or silicone, to enhance the colour play and to hide flaws. Such adsorption improvement may not be long lasting, and may be difficult to recognise (see GIA, 1995).

Glass continues to be used in efforts to imitate opal. Glass so used is called paste. Usually it can be recognised as warm to the touch, compared to cool quartz, and by the bubbles it contains (Gübelin, 1974; Gübelin and Koivula, 2004). A particularly effective imitation, devised by J. Slocum, seems to be an anhydrous silica glass internally structured to produce an attractive iridescence. This is Slocum Stone, which is quite difficult to recognise by the naked eye. However it is denser (~2.45 g/cc) than true opal, and, under low magnification, the nature of the iridescent patches and zones, which can be quite variable, differ from true opal (Anderson and Jobbins, 1990).

When buying an opal, in the absence of an expert, a valid certificate of authenticity or special laboratory tests, a curious purchaser has to gauge a specimen's provenance and purity with a 10X hand lens, experience, and trust in the probity of the vendor. A density measurement if possible, and LWUV illumination, may be helpful in evaluating Australian opal. It is easy to be deceived, so *caveat emptor*: shopper take care.

Geoscience: Australian opal fields

Currently Drs Bruce Dickson and Phil Schmidt (pers. comm.) are investigating opal formation in Australia. They note that Australia produces most of the world's precious opal yet there is no accepted model for how or when it was formed. It is a most enigmatic substance, hiding clues to its formation. Instead of focusing on the opal itself they are looking at the chemistry, hydrology, geology and palaeomagnetism of the opal areas, testing out clues as to how and when it was formed. Sammut (2016) provides an interesting discussion on the make-up and genesis of opal and opal-like (imitation) materials.

On a regional scale, Merdith et al. (2013) have produced an opal prospectivity map for Australia's Great Artesian Basin by applying a spatial data mining methodology, using G Plates Paleo GIS software. This work has identified prospective opal areas and contributed to the understanding of opal formation.

At the local scale, geophysics has been usefully applied to opal environments. The occurrence of opal is associated with claystone structures underneath or within sandstone in NSW (e.g. Lightning Ridge), South Australia (e.g. Coober Pedy), and Queensland (e.g. Yowah). It occurs as thin seams and small concretions, so it is an unlikely candidate for direct geophysical exploration. Near surface geophysics has been usefully applied in studies of the lithology and structure of host and country rocks in the opal areas. This is attested by the work of Senior et al. (1977), Whiteley (1983), Leys et al. (2001), Moore et al. (2003), Zhe and Morris (2006), and others. A three electrical layer subsurface often approximates the opal host environments. At Lightning Ridge, for instance, there is a top layer of high resistivity silcrete, ~500 ohm m; an intermediate sandstone layer ~20 ohm m; and an underlying claystone, <2 ohm m. Resistivity would seem to be ideally suited for the investigation of the main strata even though complications could be expected in the form of variable moisture contents, and small structures such as joints, faults, and shears. Whiteley (1983) noted the possible use of seismic refraction to map weathering at Coober Pedy, and magnetics to help locate opal-hosting ferruginous zones at the sandstone-claystone boundary in southwestern Queensland fields.

Little has been published on the use of Ground Penetrating Radar in exploration for opal but recently it was reported to have been successfully applied in Queensland to identify ironstone boulder zones known to occur near opal bearing horizons, and to investigate opal bearing structures, in the shallow subsurface. Excavation of identified targets resulted in the recovery of opal-bearing material. This appears to be a promising development (http://www.opalhorizon.com/News/Company Announcements.aspx).

Some physical properties of opal

Although the direct geophysical detection of opal is unlikely, the physical properties of opaline materials are worth investigating, if only for the record, as little seems to be known of its physical properties beyond density and refractive index. Keller (1966) cited values of 7.15 and 7.43 for the permittivities (dielectric constants relative to free space) of two opals from Japan. Olhoeft (1981) recommended a DC conductivity of 3.9×10^{-7} S/m and a 1 MHz permittivity of 13.01 for opal. Xu et al. (1989) investigated the electrical properties of one natural and two synthetic opals at frequencies up to 100 kHz and temperatures to 485°C. They noted that the dielectric constant of the opals exceeded that of pure silica and attributed weak conductivity affects to impurity ion migration.

Some tests (see Emerson, 2015) were carried out mainly on common opal, as the price of precious opal samples of adequate size is prohibitively costly.

Mass, magnetic, electric, dielectric, and velocity measurements were made on a limited number of samples: common and white opal from Lightning Ridge NSW and Coober Pedy SA, and boulder opal from Yowah Qld. A recrystallised, pure, fine grained Devonian quartzite from north of Heathcote Victoria (used as a proxy in the absence of a suitable quartz crystal sample), chalcedony from north of Lismore NSW, and massive, vitreous, bluish-black cristobalite from Siskiyou County, California USA, were also tested (Figure 4). Cristobalite when microspherical is a constituent of many opals.

Opal water content was investigated by Smallwood (2014) using thermogravimetric, calorimetric, and other methods. Australian

Figure 4. *Some of the opaline materials used in the physical property tests prior to shaping for the measurement jigs: top left - Lightning Ridge NSW blue-black common opal, 13.57 g, top right - Coober Pedy SA white opal, 2.95, 5.63 g, bottom left – Coober Pedy SA milky blue common opal, 10.67, 6.50 g, bottom right, – Yowah Qld boulder opal, polished 19.40 g, rough 17.23 g. Photos by Lainie A Kalnins/CC BY-SA 3.0.*

sedimentary opal heated to 1000°C had significant mass losses in the middle temperature range (several hundred °C). The mass losses ranged from between 6 to 8%. This and other data were interpreted as showing that opal typically contains about 10% bound (silanol) water, 10% molecular water in voids (~50 nm diam.) and capillary pores (~5 nm diam.), and 80% molecular water trapped in silica cages.

In the tests carried out by the writer, fresh water could not be introduced into precious and common opal specimens whether by vacuum saturation or by boiling. Furthermore, prolonged oven drying to 105°C did not release any water. So effective (water-accessible) porosities are zero. However, the occluded porosities, as described by Smallwood, are certainly present, but the release of such water would have required grinding to powder and subjecting it to very high temperature. Water resides in opal, but, being occluded, it is immobile under ordinary conditions. Stevens (1998) noted that, contrary to popular belief, Australian opal is not porous in a way that will absorb liquids.

Table 3 summarises some results. Precious and common opal has no water accessible porosity, but the boulder opal (with goethite, sand and clay matrix) has 11% porosity. Densities are in the expected range for ironstone free opals, ~2.1 g/cc, but are higher for the boulder opal owing to its iron oxide content. This iron oxide contributes to a magnetic susceptibility, 66×10^{-5} SI, which, although low, is quite distinct from the other opals with virtually zero susceptibility (slightly negative, i.e. diamagnetic, in a couple of cases).

Galvanic resistivities were measured generally parallel to any foliation and at 1 kHz on shaped materials in the air dry state. The resistivities for the common and white opals are very high, average ≈450 000 ohm m. The resistivities of the non-hydrous quartzite, cristobalite, and chalcedony are even higher than the opals. These materials are dielectrics with large phase lags between voltage and current; displacement current is dominant. The boulder opal resistivity is lower on account of networked residual moisture in the porosity and clay components. Ohmic current dominates in this material for which resistivity diminishes by an order of magnitude when vacuum saturated with fresh water.

The dark common opal and the boulder opal did not fluoresce under long wave ultraviolet light; the others did.

Given the clearly dielectric or insulating nature of the opals, measurements of real and imaginary permittivity (dielectric constant relative to free space) were carried out generally normal to any foliation or lamination and at 1 MHz. Real or in phase permittivity (K′) reflects the polarisability of mobile, semi mobile, or bound charge, while the imaginary (quadrature, out of phase) permittivity (K″) reflects the energy loss from the charge movements (Maxwell-Wagner effects, dipole rotation etc.).

Table 3 and Figure 5 give the results of these limited tests. Clearly, the low density common opal has quite a high polarisability (K′ ≈ 10) when compared to literature values for

Table 3. Measured physical properties of some opal and other opaline materials

Material	Bulk density (g/cc) (air dry)	Porosity (%)	Magnetic susceptibility Si × 10^{-5}	Galvanic Res. 1 kHz, ohm m (air dry)	Response to Long Wave Ultraviolet	Permittivity 1MHz Real K′	Permittivity 1MHz Imaginary K′	Pwave Velocity 100 kHz (m/s)
Milk opal, white Coober Pedy SA (1 sample, precious)	2.15	→ 0	→ 0	403 268	✓	10.25	1.20	4655
Common opal, blue-black, Lightning Ridge NSW (average of 2 samples)	2.11	→ 0	→ 0	593 609	✓	10.38	2.14	4818
Common opal, white Coober Pedy SA (average of 2 samples)	2.11	→ 0	→ 0	348 310	✓	8.89	1.72	5000
Boulder opal goethite matrix Yowah, Qld (average of 3 samples)	2.48	11.2	66	25 215		11.76	2.56	4844
Quartzite, Heathcote, Vic	2.62	→ 0	→ 0	728 675		4.20	0.05	6164
Cristobalite, Siskiyou, California	2.36	→ 0	→ 0	623 896		5.00	0.03	6122
Chalcedony, Lismore, NSW	2.60	→ 0	→ 0	644 000		4.00	0.10	5241

crystal quartz (K′ = 4.4), and to the measured values for chalcedony (K′ = 4.0), quartzite (K′ = 4.2), or cristobalite (K′ = 5.0). This is to be expected from the aggregate complex of hydrous and hydrated minerals and mineraloids in the voids of the opal. The denser boulder opal has high polarisability and loss too, but this is due mainly to kaolinite, goethite, and residual moisture in the open-porosity matrix. Opals are quite lossy compared to other silicas. The opals' quadrature permittivities, K′ ≈ 1.8, are far higher than the quartzite, chalcedony, and cristobalite (K′ ≤ 0.1). Opal has a distinctive physical character when compared to other silicas.

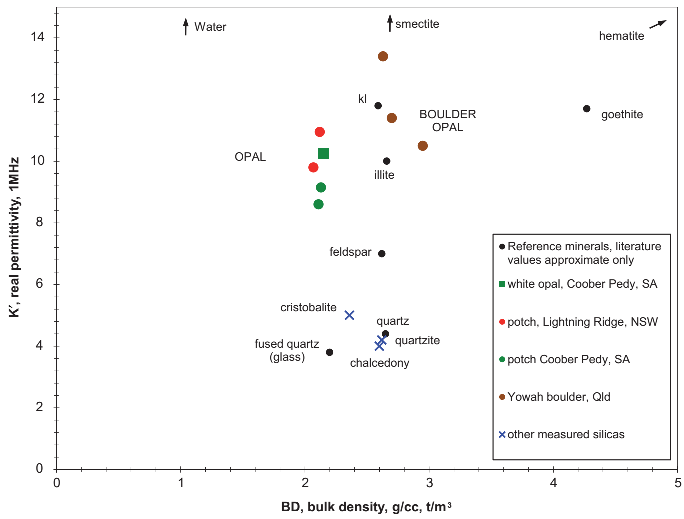

Figure 5. *A dielectric polarisability plot for real (in-phase) permittivity against bulk density measured air dry at 1MHz. The low density Australian common opal samples, owing to their hydrous nature, exhibit quite high polarisabilities compared to quartz and fused quartz. All these materials have virtually zero magnetic susceptibility. The Queensland boulder opal has a higher density and comparable polarisabilities but these arise from the iron oxide/clay matrix which holds only minor amounts of opal in seam and nodule form. The boulder opal has a magnetic susceptibility ~65 × 10^{-5} SI owing to its Fe oxide content. The reference mineral values are from Olhoeft (1981), kl = kaolinite.*

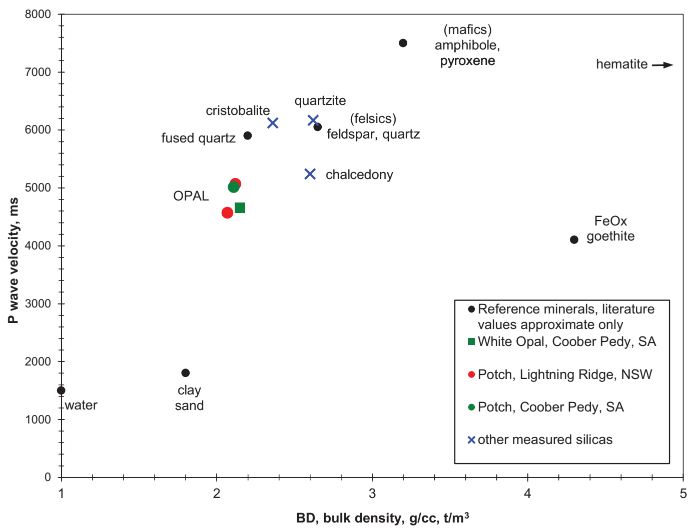

Figure 6. *A plot of compressional (P) wave ultrasonic velocity (100 kHz) against bulk density for common opal samples. The data are referenced to a notional weathered environment mineralogy. There are distinct differences in velocity and density between the opaline silicas and quartz.*

It seems that dielectric measurements could be usefully included in the suite of categorisation tests employed in opal studies.

Ultrasonic velocity measurements were carried out @ 100 kHz under 10 kN uniaxial load and generally subparallel to any foliation. The data are shown in Table 3 and Figure 6 in the perspective of the main minerals likely or possibly to be encountered in the weathered environment. Common opal is seen to have a fairly high velocity (~5000 m/s) but well below that of quartz and quartzite (~6100 m/s). The opal velocity is lower owing to its poor crystallinity, its porosity, and its mineraloid pore fill.

In addition to the mesoscale physical property indications presented here, any assessment of an opal environment's macroscale field character would need to consider energising frequencies, fracturing, and water saturation of the overall rock mass.

Remarks

The delightful sight of a beautiful iridescent opal has captured humankind from the earliest times. It is a mineral like no other. As the needle to the pole does swing, so the eye to the opal. An opal may not match a diamond in splendour, but it beats it in beauty. The abstract pleasure of an opal resides in the dynamism of its yellows, greens, blues, and reds that have no fixed form, no beginning, no end. Incomparably beautiful flashes of rainbow hues vary when viewed from different directions.

Opal's physical characteristics are distinctive, beyond its optical aesthetics. These include low density, a substantial porosity yet no permeability, quite hydrous yet very high resistivity, high dielectric polarisability compared to quartz, zero magnetic susceptibility (for the non-ironstone types), and a low compressional wave velocity compared to quartz. It is possible that the dielectric properties may be useful in the investigation of opal type and internal structure. In these quite limited tests there is not much difference between common and precious opal.

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The development of optically pumped magnetometer systems and their applications in Australia Part 1

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Introduction

Who remembers when magnetic surveys for mineral exploration required first sending out a surveyor and chain-man to clear lines and peg a grid? The pegs might have been at 5 or 10 chain intervals (100 or 200 m) along lines separated by 40 chains (800 m). The geophysicist would then have carried his magnetometer (in its beautifully made wooden cabinet) and tripod to each grid peg. He would have then set up the tripod, levelled the magnetometer using perpendicular spirit levels and peered down a microscope to read a hairline off a scale. The instrument temperature was recorded with the magnetic field value in a field notebook before the equipment was packed up and moved onto the next grid point. Usually it was a relative measure of the vertical component of the field that was obtained by measuring the torsion on a suspended compass needle and, after temperature compensation, a good operator could resolve down to 2 nT. Less than 100 measurements per day could be acquired with this technology, and this was after the more time-consuming grid pegging was completed.

During the 1950s and 60s the torsion balance, mechanical magnetometers were replaced by electronic flux-gate instruments. Now, a much lighter device could be carried to each grid peg. But this device still needed to be operated while held stationary in a vertical position as determined by a single 'bulls-eye' bubble. A relative measure of the vertical component of the field was again hand recorded after reading off an analogue meter. Measurement time was improved at the cost of resolution that, at best, was 5 nT. About 150 measurements per day was typical.

And then, in 1967, in association with Oxford University, the Littlemore Scientific Engineering Company developed the 'Elsec' Proton Precession magnetometer. This was a major advance in magnetometer technology as, for the first time, nuclear magnetic resonance enabled the absolute value of the Total Field Intensity to be acquired, not just to 1 nT resolution but in the short time of 3 seconds! Our geophysicist could now occupy a grid station, press a button, wait 3 seconds and then write down a number read off each of five analogue meters graduated in ten steps from 0 to 9. With such measurement speed 'high resolution' surveys could be conducted at 1 chain (20 m) intervals. The 'chain-man' walked ahead and dragged a 'chain' behind, and the instrument operator shouted 'stop' each time the end of the chain reached a scrape in the ground indicating an in-fill measurement point. An operator using such an instrument during the 'Nickel Boom' of the late 1960s was proud to be able to acquire as many as 750 measurements in a day. But, the day was not yet done. These measurements then had to be hand plotted as profiles and often contoured or, maybe, typed into a card punch and fed into an office mainframe computer. Even in the latter case, while mainframes were connected to a typewriter/printer, how many were connected to a plotter? And, who had software to perform contouring? A well respected archaeological team at Oxford University used alpha-numeric characters on their printer in an attempt to create a 'grey scale' image of their magnetic data where a '.' would represent a low value, light grey, and a 'W' would use more ink and create a darker impression. Magnetic mapping was still time consuming, with the effort required to determine the location where the measurements were acquired contributing significantly to data acquisition time, and methods for presenting data in an interpretable form were slow and primitive. Moreover, measurements taken no closer than 20 m apart could only be used to properly define target sources deeper than 20 m as shorter wavelength anomaly components arising from shallower sources would be under-sampled and their energy folded back into the profile as noise. This was 'state of the art' in the late 1960s.

Establishment of a Geophysics Department at the University of New England, Armidale

In 1967 Ron Green was appointed to the University of New England with the task of establishing a Department of Geophysics. Ron's vision was for a Department that would specialise in the physics and mathematics that were at the heart of geophysical exploration data acquisition and data analysing technologies. His goal was to produce graduates that were equipped to design and develop the next generation of instruments and data processing technologies, or to go into industry capable of solving the multitude of site-specific problems that were confronting this newly emerging exploration frontier in our challenging, regolith dominated Australian environment. Ron didn't want to just train exploration practitioners to apply off-the-shelf technologies (developed in Canada or Scandinavia where geological conditions were very different and far more favourable), he wanted to produce problem solvers. Giving priority to physics and maths over geology did not best suit the requirements of all sectors of the industry. But, given that Ron's graduates from the short, 15 year life of his Department have received 6 of the 14 Grahame Sands Awards given by the ASEG for Innovation in Applied Geoscience, Ron clearly identified an important need in our industry at the time and he fulfilled it admirably.[1]

Ron had a small budget to purchase some exploration instruments and he chose to spend this on a 'state-of-the-art' Elsec magnetometer. He also solicited the donation of unrequired equipment from industry, as this would give his students a hands-on introduction to the principles behind the range of methods used at that time for sub-surface exploration. Initially Ron's Department concentrated upon offering a quality Honours year program to graduates strong in physics and either maths or geology. Students with no geology were required to take some geology subjects during their Honours year. He later introduced Masters and Doctorate programs. While he taught geophysics at undergraduate level, his emphasis was on establishing a Post Graduate Department.

John Stanley (the author of this article) and Jim Cull finished Physics Degrees at Monash University in 1968 and chose to join the emerging field of geophysics. They enrolled in Ron Green's Honours program. Both John and Jim had good undergraduate records in the practical components of their degree. In the light of this, Ron proposed that for the major research element of their Honours study they collaborate to apply the principle of 'Optical Pumping' described by Kastler in 1950 to the application of measuring the Earth's magnetic field (Kastler, 1950).

John and Jim soon understood the requirements of their task and knew that at first they would need to devise a very stable, noise free source of spectral light at the D1 wavelength corresponding to the first excited state of the single outer electron of the alkali Cs atom. They would also need an 'absorption cell' containing a vapour of Cs metal. Cs is a liquid at room temperature and its vapour pressure was believed to be sufficient for the purpose. But, Cs is highly reactive, demanding that a silica lamp bulb and absorption cell be completely sterilised of impurities if their life containing free Cs was to be prolonged.

With these components a self-oscillating system was proposed whereby the optical transmission of circular polarised D1 light through the absorption cell could be monitored with a photocell to detect the optically pumped condition (cell transparent). If this signal was amplified and fed back with a suitable phase shift into a coil wound around the absorption cell parallel to the light beam it would cause the cell to 'depump' (making it relatively opaque). With such feedback the pumping/depumping cycle should resonate at the 'Larmor Frequency', known to be proportional to the intensity of the ambient, Earth's magnetic field. Once resonating, the Larmor frequency would be determined and a measure of the Earth's Total Field obtained. It all sounded pretty straightforward!

The attempt to construct an optically pumped Cs, alkali vapour magnetometer in the course of an Honours project proved over ambitious, but two significant achievements were attained. Jim determined that an appropriately stable and noise free source of D1 light should be obtainable from the radio frequency excitation of Cs vapour in an evacuated glass bulb. He successfully constructed a radio valve operated oscillator running at 200 MHz, this being significantly higher than the Larmor resonance frequency of the Cs D1 electron transition in the Earth's field, this being less than 200 kHz. John applied himself to the production of a highly evacuated lamp bulb and absorption cell. These were to contain a trace of free Cs metal and an inert gas to dampen collisions between the Cs vapour and the cell wall. Due to the highly reactive nature of Cs, the major problem of sterilising the quartz glass cell had to be overcome, and it was (Clack and Stanley, 1971). They now had a suitable working lamp and absorption cell, each with a long life expectancy. In fact, a lamp bulb made in 1970 is still producing Cs spectral light in 2016.

The prototype Cs magnetometer

In 1970, John Stanley resumed the task of developing a Cs Vapour magnetometer, now as part of full-time research towards a Doctoral Degree. By the year's end, he had a self-oscillating system working, with the valve driven lamp oscillator now replaced by a transistorised one running at 130 MHz. This achievement had been frustratingly delayed during the winter of 1970 as the importance of heating the Cs to increase its vapour pressure had not yet been appreciated and the research laboratory in Armidale in winter without air-conditioning was very cold!

With a self-oscillating sensor system now working, (Figure 1) it was practical to determine experimentally the cell temperature at which the vapour pressure of Cs in the absorption cell would deliver optimal optical pumping signal. This was found to be 50°C and the sensor was then packaged with a 'zero field' bifilar heating element running at 2 kHz surrounding the absorption cell. The sensor, containing the lamp, heated absorption cell, feedback coil and optics, was then linked by mini-coaxial cables with its control electronics at such a distance as to eliminate magnetic interference from the electronics (1500 mm).

[1]In 1973 Dane Blair, a PhD student under the supervision of Peter Sydenham in Ron Green's Department, set out to develop a laser interferometer strain gauge for use in measuring strain in the Earth's crust from an underground observatory in a disused gold mine at Hillgrove. The use of such a device to detect gravity waves was considered. While Dane's development was an important precursor to this application, it took another 40 years of refinement (by others) before this application was successfully realised.
Andrew Hugill, also under the supervision of Peter Sydenham, set out in 1977 to develop a new transducer to be applied to the measurement of gravity. Andrew delivered a working prototype that he then further developed while employed by Scintrex in Canada. The CG-3 and its later upgrades through to CG-5 have become the industry standard in ground based and borehole exploration using gravity. Andrew's innovations significantly increased the speed with which gravity data could be acquired, thereby reducing the cost of acquiring higher detail in gravity mapping.
Jim Cull, after graduating with Honours in 1970 became exceptionally successful in both industrial and academic environments by applying sound physical principles with innovation and practical application to a diverse range of geophysical instrumentation developments. His achievements culminated in the award of an Order of Australia medal. It was the specific development of an electromagnetic receiver and processor that earned Jim Cull and Duncan Massie the 2006 ASEG Grahame Sands Award for innovation in applied geoscience. Phil Schmidt graduated with Honours in 1972 and after gaining a PhD from ANU in 1976 pursued a research career with CSIRO, always working closely with instrumentation development. Phil Schmidt was recognised with the 2015 ASEG Grahame Sands Award for his development of a 'Q meter', a field portable instrument for measuring the magnetic properties of rock samples, providing information of great practical value in the interpretation of magnetic survey data.
Malcolm Cattach and John Stanley were given the 1988 ASEG Grahame Sands Award for the development of the TM-3 magnetometer and the 1995 ASEG Grahame Sands Award for the development of Sub Audio Magnetics, a method by which both magnetic and electromagnetic data could be simultaneously acquired using a TM-4 magnetometer. Malcolm Cattach, Keith Mathews, Ed Campbell and Symon Bouwman were given the 2013 ASEG Grahame Sands Award for the development of the GeoPak HPTX-70 high power electrical transmitter.
In 2007 John Stanley and Malcolm Cattach were awarded a Comenius University Medal for their contribution to the science of exploration geophysics. Comenius University in Slovakia is where, under the Austro-Hungarian Empire, the first Academy of Mining was established in 1735. This academy later became the first Technical University in the World.

Figure 1. *The prototype Cs vapour magnetometer sensor with discrete component transistorised circuits (1971).*

Attention was next directed to counting the Larmor Frequency and converting this to magnetic field units (Figure 2). By 1971, TTL logic chips had just become available and a fully digital system was envisaged, although a non-volatile digital memory medium was not yet available. Given that the Larmor Frequency varied by 3.49869 Hz per nT, a frequency counter that used a timing gate the reciprocal of this value (0.2858 s) would yield a count numerically equal to the magnetic field in nT. A timing gate 10 times wider (2.858 s) would deliver a count in units of 0.1 nT. While these sample rate and resolution figures were a factor of 10 improved over the Elsec magnetometer, the use of a period counter rather than a frequency counter was recognised as better able to take advantage of the characteristics of the new sensor and deliver a faster measurement rate. By using the Larmor signal to gate a high frequency clock, 0.01 nT resolution could be delivered in approximately a 2.2 s period, 0.1 nT in 220 ms or 1 nT in 22 ms (Stanley et al., 1975). The objective now was to develop applications that would benefit most from these enhanced characteristics.

Figure 2. *The first 'digital alkali vapour magnetometer using integrated circuits'. The release of TTL digital logic integrated circuit devices permitted a magnetometer to be built in 1973 that took the Larmor signal from an optically pumped sensor, and from this determine a digital measure of the Total Magnetic Intensity. A 1 nT resolution could be updated approximately 45 times per second.*

Initial applications of the enhanced magnetometer characteristics

While the high resolution characteristic of the Cs sensor would have application in global geophysics and space science, John recognised the fast sample rate as having the most potential for making sub-surface mapping in geophysical exploration cost and time-efficient. However there was an urgent need to overcome the constraints imposed by conventional survey grid position measurement. Magnetic field values and the location where they were acquired had to be recorded automatically and achieving this became John's priority.

a. Technology for magnetic mapping at an archaeological site scale

An interest in archaeology led John to investigate the feasibility of magnetically detecting pre-historic camp fires through the conversion of less magnetic Fe_2O_3 (haematite) to the more magnetic Fe_3O_4 (magnetite) in the reducing environment of the campfire hearth. To do this, a 26 ft × 14 ft (8 m × 4.25 m) area was to be magnetically mapped before and after a campfire had been lit and let burn for 24 hours (Stanley, 1976).

The Cs sensor was able to be operated from a cable up to 30 m from the counter electronics. A stepper motor was fitted to a chart recorder and this was interfaced to an analogue output port from a D to A converter following the digital period counter in the magnetometer. An odometer was built in which a string from a spool passed around a 318 mm disc which had 100 optical slots at 10 mm intervals around the circumference. The sensor carrier would draw the string out from this odometer as an 8 m length straight line traverse was made across the survey area. As the odometer disc rotated, a light beam was chopped producing trigger pulses to step the chart recorder motor. In this way a scalable record proportional to the distance traversed along a grid line was automatically plotted. At the end of an out-bound survey line, the sensor carrier would move 100 mm across grid, and the recorder operator would then 'wind the string back' as the return grid line was mapped. The 8 x 4 m test area was mapped this way before and after the camp fire was lit. Each coverage automatically logged (in analogue format) effectively 40 000 measurements each to 1 nT resolution. This was achieved in a survey time of just one hour.

How was this data presented? It was an analogue record and individual profiles could be interpreted using the graphical methods of the day. However, by tracing each profile with a small, scaled offset progressively from one edge of the survey area to the other, and with the application of a 'hidden line' where a later profile fell below the topography of a previously traced line, a pseudo 3-D isometric image of the data was generated (Figure 3). It was noticed at the time that this presentation was very effective in enhancing those magnetic features that were continuous between survey lines while supressing the effect of random and temporal noise. This presentation provided a primitive form of image processing and was the precursor of computer generated isometric images that followed soon after.

The success of this experiment led to the use of the odometer system in larger archaeological surveys where areas measuring up to 25 m along line by an unconstrained distance across line were conducted. In this case the 25 m along-line limitation was imposed by the maximum cable length of 30 m permitted between the sensor and its control electronics.

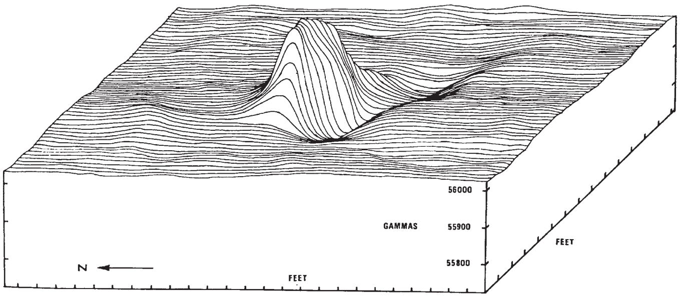

Figure 3. *A pseudo isometric image of the magnetic field recorded over a fire hearth that had been left burning for 24 hours. The image was produced by tracing analogue profiles automatically plotted during data acquisition, each with a scaled offset from the front of the image to the back. (1 gamma = 1 nT).*

Archaeological surveys very effectively mapped sites of early aboriginal occupation with some fire hearths dated 29 000 years before present being detected. The magnetic disturbance associated with a fire hearth was found to be attributable not only to the reduction of iron oxides in the soil, but also to remnant magnetisation acquired when the hearth temperature cooled after exceeding about 600°C. The very high spatial resolution (high definition) of these surveys also revealed the considerable amount of near-surface geological information that was available and which could now be acquired efficiently. This observation was not forgotten!

b. A vehicle-borne magnetometer system

In 1972 the only practical field portable means for recording rapidly sampled data was using the medium of an analogue chart recorder. Having installed a stepper motor in a chart recorder for the archaeological mapping application, fitting a Hall device switch to the tail shaft of a Land Rover enabled data to be plotted at selectable scales at known distance increments along a driven survey line. Upon mapping the magnetic field around the Land Rover in planes at different elevations above ground, it became apparent that a plane existed approximately through the centre of gravity of the vehicle, in which, just 6 m from the vehicle centre, the contour of uniform interference due to the steel in the vehicle was close to circular. This meant that if the sensor was mounted on a non-magnetic stinger 6 m from the centre of the vehicle the heading error would be minimised (Figure 4). In fact, at this distance, the heading error for a 360 degree rotation was 25 nT peak to peak or approximately 0.07 nT per degree of heading change. As long as the vehicle was driven in a reasonably straight line an acceptable level of heading error would be encountered. Pitch error was found to be similar. A Series 1 short-wheelbase Land Rover was fitted with such a stinger, an odometer switch, power supplies and a chart recorder modified with the inclusion of a stepper motor (Stanley, 1975a). Data could be acquired at 0.25 m intervals while travelling at 40 kph.

Experience with this system in reconnaissance transects across NSW in 1973 resulted in two significant observations. It was noticed that present and prior water courses were frequently associated with a magnetic disturbance due to the concentration of heavy, magnetite rich sands (Stanley, 1975b), and it was documented that many different near surface geological units were characterised by their own, unique 'magnetic signature' (Stanley, 1975a).

c. Portable digital recording

While the first vehicle-borne Cs magnetometer system had (within the limitations of requiring straight line survey transects)

Figure 4. *The vehicle-borne magnetometer in which the Cs magnetometer sensor was mounted in a plane where the contour line of interference from the vehicle's magnetic field was almost circular. The result was a heading error of just 0.07 nT per degree. Magnetic data were automatically logged to scale on a chart recorder triggered from the vehicle odometer. Measurements were acquired at 0.25 m intervals while travelling.*

overcome the problems of automatically assigning a position to each rapidly sampled magnetic measurement, the benefits of digital recording were anticipated, but not as yet available. In 1972, the microprocessor, PC and portable non-volatile memory were still to be invented.

In 1978, the Geophysical Research Institute (GRI) was formed within Ron Green's Department.[2] The objectives of this Institute were three-fold. John, with Ron's support and encouragement argued that:

i. At a time when the exploration industry was confronted with many limitations resulting from the inherent unsuitability of existing geophysical instrumentation for the conductive and magnetic regolith dominating much of our continent, research done in Australia should address identified needs of industry rather than be in pursuit of some purely academic interest.
ii. Research projects that addressed the specified needs of an industry player would benefit from access to current exploration sites, logistical assistance with fieldwork, financial support, and the input of the practical experience of the company's representative. This latter contribution would significantly complement the exploration related project supervision available from Ron and John. At this time the Department had but three academic staff.
iii. A third benefit from involvement with the exploration industry was that the major companies had the latest in equipment and this was mostly outside the resources of a

[2] In 1983, after just 15 years operation, the Geophysics Department was closed and amalgamated with the Geology Department.
In 1984 the GRI became an autonomous, self-funding research entity. John Stanley became its Director in 1985. A private company, Geophysical Technology Pty Ltd, was formed in 1986 by John Stanley and Malcolm Cattach to manufacture instrument developments originating from the GRI. In 1996, through a management buyout, Geophysical Technology acquired the assets and intellectual property of the GRI and commenced trading as G-tek Pty Ltd.
In 2005 John retired and Mal, with key staff, restructured the G-tek business as Gap Geophysics Pty Ltd, now based in Brisbane. Under Mal's leadership Gap has thrived, expanding into a group of businesses addressing a range of applications. These include; manufacture and development, provision globally of ground and airborne exploration services, and the delivery globally of geophysical solutions to environmental problems. Fundamental to this group's success has been their understanding of the underlying science and an on-going commitment to improving their core technologies and to developing new applications. Today all of John and Mal's aspirations for the GRI from the early 1980s have been achieved, and achieved in a manner that has established the line of exploration technologies based upon the Cs magnetometer sensor as universally accepted state-of-the-art.

small department to acquire. If research students could have access to this equipment then research into processing and interpretation of the data acquired, or indeed, research into overcoming the technical deficiencies of this equipment, would be greatly facilitated.

With the formation of the GRI, the vehicle-borne magnetometer system received a major upgrade. The 'home made' Cs sensors that had been used in the pioneering investigations could now be replaced by a military grade product recently released from US classification and now available from Varian Associates 'to friendly allies'. A new product from Sonotek in Canada employed a Z80 microprocessor in a digital data logging and replay capacity with acquisition programs and data logging being interfaced with a digital cassette tape recorder (Figure 5). This 'advanced technology' deserved the suspension and dust free environment of a Range Rover and the University advanced the funds to buy this.

Figure 5. *With the advent of the microprocessor, a digital data logging and replay facility was added to a vehicle mounted survey system. Data acquisition programs and data logging were now interfaced with a digital cassette tape recorder.*

The Range Rover supported digital system rapidly won the favour of key organisations in the minerals exploration industry. By now the highest quality data was preferred, obtained when the sensor was hand-carried some 30 m behind the logging vehicle and connected by a cable. With the 'walker' and 'driver' alternating, 40 km of survey could be acquired in one day with samples logged at 250 mm intervals. The vehicle was soon asked to push survey lines through some extremely rough terrain and heavily vegetated environments. The GRI Range Rover became readily recognisable by its golf ball textured aluminium panels. How could this data acquisition be done better?

In 1978, Honours student Stephen Lee was given the challenge to code the digital count from the Larmor signal using an audio frequency code that could be sent by CB radio back to the base vehicle. Stephen achieved this using 'Frequency Shift Keying' with zeros being represented by a chirp at 1 kHz and ones by a chirp at 2 kHz. At the vehicle, the signal was de-coded and logged on the Sonotek facility as before. Of paramount importance was the inclusion of a hand-carried odometer device to enable the automatic recording of measurements at known intervals along line. The string and pulley principle used in the archaeological investigations was adapted into a system that used a 'lost thread' of biodegradable cotton. This principle was also used in the Hip Chain that became available at the same time. Its advantage over the string system was that survey lines could now be of unlimited length. The system, called a 'Telemetric Magnetometer' model 'TM-1' achieved its objective so long as integrity was maintained in the radio link.

In 1979 Sony released their first 'Sony Walkman', a portable, robust little stereo cassette recorder. A Sony Walkman soon replaced the troublesome CB radio. The position referenced, FSK coded magnetic data were now recorded on one track of the cassette while voice comments were recorded on the other. This latter facility enabled positioned geological observations to be simultaneously recorded. The Walkman tapes then had to be replayed in real time, for logging on the vehicle-borne data acquisition system prior to downloading to a mainframe. The TM-1 was probably the first portable magnetometer with inbuilt memory (Figure 6). It certainly was the first with the capability to automatically record position with each magnetic measurement and to do so in sub-m intervals at traverse speeds faster than the operator could walk.

In 1980 the TM-1 prototype, modified to use a cassette tape recorder instead of a CB radio link, was upgraded. Use was now made of the Varian module that supplied power to the sensor, that had its own inbuilt frequency counter with serial output port (0.1 nT at 10 Hz), and a digital display. The Varian module also provided an audio tone proportional to the Larmor Frequency.

Figure 6. *The 'telemetric magnetometer' TM-1 encoded digital data in an audio code suitable for transmitting by CB radio to the vehicle-borne digital data acquisition system. With the advent of the Sony Walkman cassette recorder in 1979, the troublesome CB link was replaced. The instrument shown here was the first portable magnetometer with inbuilt memory and a data positioning device.*

This latter feature not only alerted the operator to magnetic anomalies being traversed, but it also provided a valuable monitor should the orientation of the sensor drop out of its operating zone. Data from a serial port on the Varian module was FSK encoded as was done in the prototype and then recorded in real time using one of the two stereo tape tracks. As with its predecessor, the second tape track was used to record voice notes of observations relevant to the interpretation of the magnetic data. The TM-2 was a robust and compact little unit that performed many thousands of survey km (Figure 7).

Figure 7. *In 1980 the TM-1 prototype was upgraded using facilities available in the Varian sensor controller/frequency counter module. Digital data and voice notes were recorded in real time at sample intervals automatically determined by a cotton thread type odometer. Positioned measurements at sub-metre intervals could be acquired at survey speeds faster than the operator could walk.*

d. Technology for explosive ordnance detection

After the successful detection and mapping of pre-historic campfire sites, curators of the world's largest public collection of Thai ceramics held at the Adelaide Museum of Fine Arts asked if the TM-2 could be made available to search for buried pottery kilns at the site of an archaeological study in Thailand (Hein, 2001). Their problem was that all visible kilns had been plundered for the tourist trade, destroying their originality and

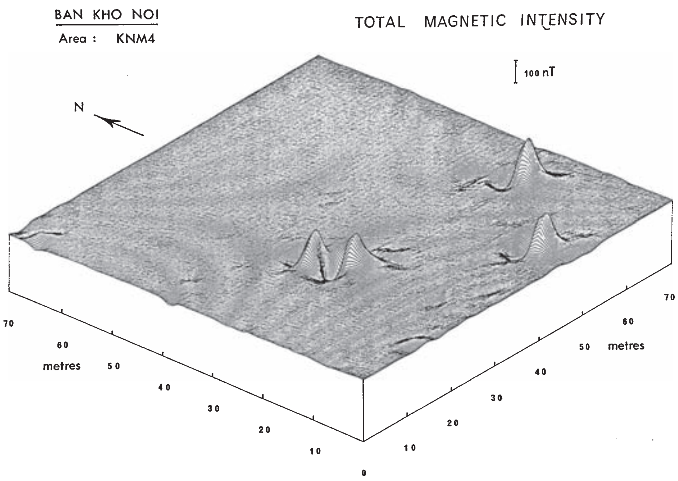

Figure 8. *The magnetic field mapped in Thailand in 1984 with a TM-2 magnetometer. The four anomalies visible indicate the location of four pottery kilns from the Sukhothai period of 1250 to 1500 AD.*

Figure 9. *A shallow, 15th century, Thai pottery kiln measuring about 5 m x 3 m during excavation after being detected with a TM-2 magnetometer in 1984.*

making them unsuitable for research into the kiln technology itself. Finding kilns that had been buried by the regular deposits of river flood alluvium over the last 1000 years was desired. In 1983 and 1984 John used a TM-2 to map many hectares of river flood plain at a data density of 50 000 positioned measurements per ha (Figure 8). By virtue of great luck, one of the first kilns discovered was found to have collapsed during firing and had been abandoned. These kilns measured some 5 m in length and 3 m width (Figure 9). During firing, these kilns are maintained at approximately 1200°C. So, when a kiln collapsed it was easier to move on and build another. But this kiln had collapsed late in the firing process and inside were hundreds of almost perfectly glazed items. Some were large water urns that at 1200°C were quite plastic and had become deformed (Figure 10). Inside and well protected there were also dozens of beautiful lamps and vases in perfect condition. As a second incidence of luck, the BBC were passing through the area at the time, documenting the footsteps of Reginald le May, an early British official who had reported signs of a significant pottery industry. Here before their cameras was a pristine example! The film crew were also impressed by, and gave credit to, the role that new magnetometer technology was playing in this project.

The day following the BBC documentary going to air in 1984, John got a call from a representative of the RAAF. He said: 'If

Figure 10. *Excavation of a kiln that had collapsed during firing in the 14th Century. Visible are two large water urns. Inside these were many undamaged oil lamps and vases. The BBC cameraman can be seen scoping the angles for filming.*

you can find 1000 year old pottery kilns then surely you can detect 1000 lb bombs – and we have lost a few'. The TM-2 was then contracted in 1985 to map an 80 ha dis-used bombing range area in Darwin for the purpose of detecting unexploded ordnance (UXO), prior to making the area available for civil use as the municipal garbage dump. The particular problem confronting the RAAF in Darwin was the high incidence of magnetite in the lateritic hill-top target area. Conventional metal detector systems failed to resolve between signal and noise from the geology. With digital data, appropriate filtering and discrimination provided visually from isometric images, UXO were detectable amongst the background interference. The success of this project led the Australian Department of Defence in 1986 to contract Geophysical Technology, a spin-off from the GRI, to build and supply a system for unexploded ordnance detection. This system had to include both robust hardware and a data processing stream implementable on a PC that would provide an audit trail for quality assurance purposes. Prior to this development an operator using an analogue detector might be assessed by what he had found each day, but no-one had any idea what he might have missed. In reality the operator may have had the instrument turned off and no one would know! Little was it appreciated at the time that the quality processes developed at the GRI for the RAAF would have a global impact just a few years later when the Iron Curtain fell and world-wide there emerged a need to clean up former Defence sites so that land could be handed back to the public with a reasonable certificate of assurance that the ground was safe.

Critical to the success of this contract was the contribution that Malcolm Cattach made in developing operational and data analysis software, the latter able to be run on a PC. The new 'TM-3' had an inbuilt Z80 microprocessor based data acquisition system using now available solid state memory, input and counters for 2 Cs sensors and a cotton thread type odometer (Figure 11). Software running on the system had the facility to calculate a linear correction for cotton thread stretch using known control points along line. Positional error along line was now reduced to approximately 0.2% of the distance between control points, or 100 mm when control lines were set at 50 m intervals. Data stored in memory could be output via a serial port. One ha could be mapped by two operators with 100 000 positioned measurements in under four hours. The era of the PC had now arrived and Mal developed data imaging software involving colour mapping and isometric plotting, the benefits of which in signal recognition from background noise had already been appreciated. Three-dimensional data inversion over identified targets permitted the position, depth and approximate size of items requiring investigation to be defined and recorded for quality process purposes.

The contribution of the TM-3 to the expanding application of magnetic mapping was recognised by the ASEG in 1988 when John and Mal became the recipients of the first Grahame Sands Award for Innovation in Applied Geoscience.

Figure 11. *The TM-3 magnetometer with microprocessor controlled survey management aids, inbuilt odometer and digital recording from up to two optically pumped sensors.*

Editor's note: John Stanley's fascinating account of the development of optically pumped magnetometer systems and their applications in Australia will continue in the next issue of *Preview*, in which John will describe the diversification in the applications of optically pumped magnetometers and development of SAM and SAMSON.

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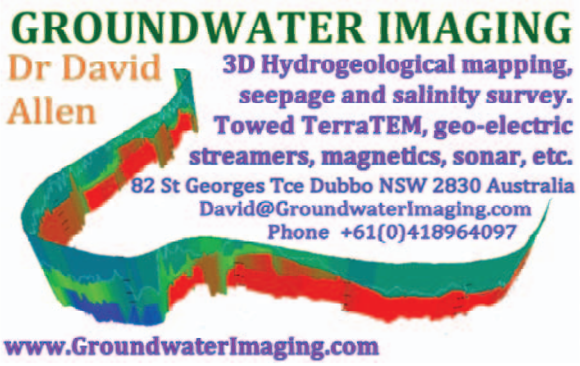

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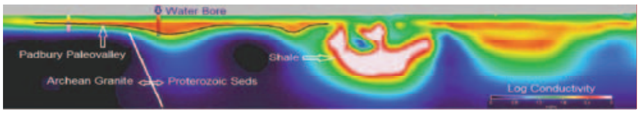

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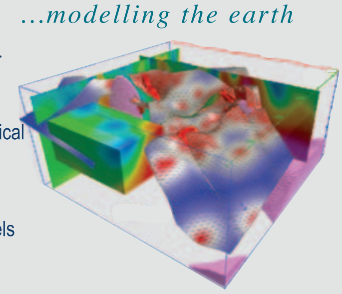

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12–15	79th EAGE Conference and Exhibition 2017 http://www.eage.org/	Paris	France
July	**2017**		
31 Jul–3 Aug	15th International Congress of the Brazilian Geophysical Society and the EXPOGEf 2017 http://sys2.sbgf.org.br/congresso/	Rio de Janeiro	Brazil
September	**2017**		
3–7	23rd European Meeting of Environmental and Engineering Geophysics Near Surface Geoscience 2017 http://www.eage.org/event/	Malmö	Sweden
3–7	Second European Airborne Electromagnetics Conference Near Surface Geoscience 2017	Malmö	Sweden
10–13	SAGA 2017 15th Biennial Conference and Exhibition www.sagaconference.co.za	Cape Town	South Africa
12–14	Offshore Site Investigation and Geotechnics Committee (Society for Underwater Technologies) 8th International Conference http://www.sut.org/specialist-interest-group/osig-offshore-site-investigation-and-geotechnics/	London	UK
24–27	SEG International Exhibition and 87th Annual Meeting http://www.seg.org	Houston	USA
October	**2017**		
8–12	International Conference on Engineering Geophysics (ICEG)	Al Ain	UAE
15–18	AAPG/SEG International Conference and Exhibition http://www.aapg.org/events/conferences/ice/announcement/articleid/5666/aapg-seg-2017-international-conference-exhibition	London	UK
21–25	Exploration '17 http://www.exploration17.com/	Toronto	Canada

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