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Australian Society of Exploration Geophysicists

PREVIEW

NEWS AND COMMENTARY

Vale Barry Drummond

New ground released in Victoria

New data available in South Australia

Business investment in R&D

Stratal slicing

Web page auditing

FEATURES

Summaries of 2019 student theses

Pyrite – the firestone

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ADVERTISERS INDEX

ASEG CORPORATE PLUS MEMBER

ASEG CORPORATE MEMBERS

FRONT COVER

The *Salt River* with the marine MT instruments on deck leaving Port Lincoln for the Spencer Gulf. See the report by the Geological Survey of South Australia in this issue for more information

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Editor's desk

This Christmas issue of *Preview* is bulging at the seams. We are blessed, once again, with a Don Emerson special – this time on "Pyrite- the firestone". I, for one, am hoping Don never retires. Reading his Christmas contribution over a glass of red wine has become quite a Yuletide tradition!

We say goodbye to Barry Drummond in this issue, but celebrate AINSIR, just one component of Barry's rich legacy to Australian geophysics. We also say goodbye to Sheldon Breiner, an entrepreneurial geophysicist who had a finger in a surprising number of pies.

We look to the future with Michael Asten (*Education matters*) and our annual summary of theses in geophysics submitted to Australian universities. Who knows, one of the featured students may prove to be as productive as Barry, or as inventive as Sheldon.

David Denham (*Canberra observed*) reports on the latest figures on business investment in R&D – not good news. On the other hand, he does have good news about the steady upward trend in exploration for gold (following the upward trend in gold price and production). Mike Hatch (*Environmental geophysics*) and Yusen Ley Cooper revisit EMusic. Terry Harvey (*Minerals geophysics*) muses about changes in how exploration companies tap in geophysical expertise. Mick Micenko (*Seismic window*) reviews stratal slicing. Tim Keeping (*Data trends*) guides novice users through petrophysical databases, and Ian James (*Webwaves*) discusses web page auditing using Lighthouse.

Next year, 2020, is the 50th anniversary of the establishment of the Australian Society of Exploration Geophysicists – our Society. *Preview* will be celebrating the anniversary by asking the ASEG President and current and past Editors of *Exploration Geophysics* to nominate their "best of" papers published in *Exploration Geophysics*. We will republish the papers with an introduction that explains why they were chosen. I am really looking forward to discovering what papers get editorial guernseys!

Before signing off for the year, however, I would to thank all regular *Preview* contributors, particularly the Associate Editors, for their support. *Preview* – your magazine – would be nothing if not for them and their willingness to put finger to keyboard, ready or not, month after month. Drinks on the ASEG at the next conference I reckon!

A safe and happy festive season to you all!!

Lisa Worrall
Preview Editor
previeweditor@aseg.org.au

Subscribe to *Preview* online

Non-members of the ASEG can now subscribe to *Preview* online via the ASEG website. Subscription is free. Just go to https://www.aseg.org.au/publications/PVCurrent to sign up. You will receive an email alert as soon a new issue of *Preview* becomes available. Stay informed and keep up-to-date by subscribing now!!

NB: ASEG Members don't need to subscribe as they automatically receive an email alert whenever a new issue of Preview *is published.*

President's piece

PESA-ASEG-AIG Presidents working together at AEGC 2019 Perth. From left to right, Nathan Parker (PESA), Ted Tyne (ASEG), Tim Pippett (for Andrew Waltho – AIG).

Another year's end is fast approaching and, for many of us, it's a time to reflect on our Society in 2019 and consider our goals for the year to come.

We have entered our 50th year as a learned society and 2019 marks some major milestones:

- ASEG's 50th anniversary year – celebrations now commencing for 2020!
- 50 years of publishing the ASEG technical journal *Exploration Geophysics* Vol. 50;
- 40 years of successful ASEG Exploration Geophysics conventions (27th ASEG Exploration Geophysics Conference & Exhibition);
- 2nd Australasian Exploration Geoscience Conference and Exhibition – a highly successful conference, delivered through the ASEG-PESA-AIG partnership, attracting around 1200 delegates and delivering outstanding Exploration Geoscience Technical Programmes, Workshops, Field Excursions and Social Events;
- 33 years of publishing the ASEG's flagship geoscience magazine with publication of *Preview* Issue 200 in June 2019;
- 30 years of direct support to exploration geophysics research and training at the Honours, MSc and PhD levels through the ASEG Research Foundation, which has now contributed around $1.5 million over the period to more than a 100 highly successful research projects with outcomes supporting exploration success.

In addition to these major milestones, our ASEG Federal Executive for 2018-19 led by Marina Costelloe, our distinguished Past President, our current ASEG Federal Executive for 2019-20, State/Territory Branch Presidents and Committees, ASEG Conference Organisers and our Editors and Associate Editors for *Exploration Geophysics* and *Preview* – all incredibly dedicated volunteers - have delivered on key goals and made positive improvements across the Society's operations:

- Delivered solid financial results overall from 2018 through 2019, positioning our Society with a secure financial base for 2020/21, including finalising the very positive business outcomes for the 1st AEGC 2018 in Sydney and forecast (at this time) positive financial results for the 2nd AEGC 2019 in Perth;
- Further strengthened our partnership with PESA and AIG on the forward schedule of AEGC conferences and exhibitions;
- State/Territory Branches have delivered a number of outstanding Distinguished Lecture Tours along with a fabulous programme throughout 2019 of monthly technical presentations and great social events;
- Actively promoted STEM Initiatives and diversity in geoscience;
- Established important leading practice changes to the ASEG Constitution;
- Updated the ASEG's Code of Ethics and the ASEG Procedures and Policies;
- Transitioned to our new publication arrangement with Taylor & Francis Australia;
- Strengthened our partnerships and formal working programmes with international affiliate societies including the SEG, EAGE, SEGJ, KSEG and SAGA, in addition to regular engagement with other international affiliates;
- Strengthened our national geoscience promotion and partnership with other member societies of the Australian Geoscience Council (AIG);
- Established a strong programme of communication to Members and beyond though our new ASEG Monthly Newsletter and social media platforms.

And last but not least …

- Released the 2019 ASEG Wine Offer – the South Australian and Victorian Branches have worked passionately to deliver an outstanding selection!

The after-glow of our successful AEGC 2019 in Perth has still not diminished for me – exploration geoscience was the real winner from this conference and the awards at the close of the Conference showcased an outstanding body of innovative science and new exploration thinking.

David Annetts, our President Elect, has been working closely with the AEGC 2019 programme organisers and our partner societies to compile all of the oral and poster abstracts and extended abstracts for release as part of the ASEG Extended Abstracts collection, via the Taylor & Francis site.

In the last issue of *Preview*, I pointed to the very positive working partnership between PESA, AIG and ASEG, which aims to build the AEGC into Australia's leading exploration geoscience conference. Indeed, there has been strong tripartite collaboration in

appointing the Conference Co-Chairs for AEGC 2021 Brisbane, and the three Presidents are working together to support the Conference Organising Committee. At this stage the strategic business arrangements are being finalised, including the appointment of Arinex as the AEGC 2021 Professional Conference Organiser. Planning is in good shape.

Also, in the last issue of *Preview* Steve Collins, in his letter to the Editor, raised his concerns on the scheduling of AEGC 2019 and perceived clashes with other significant exploration and mining events. Steve suggested a rethink on the current 18-month interval between each conferences to a biannual schedule. I very much appreciate Steve's opinion, given his long-standing contributions to the ASEG and I will certainly discuss Steve's views with our partner societies.

The underpinning for the ASEG-PESA-AIG partnership model for AEGC conventions is the imperative for advancing the integration and application of contemporary exploration geoscience both in Australia and beyond and also across the mineral and petroleum exploration sectors and environmental, groundwater and near-surface geoscience applications. In every sense, this is an event that attracts exploration and more general geoscience practitioners worldwide.

At this stage, the 18-month schedule for conferences is locked in for the two next conferences: AEGC Brisbane is scheduled for April 2021 and AEGC Melbourne will be scheduled for August/September/October 2022 (depending on convention centre availability).

This issue of *Preview*, our Christmas Issue, is loaded with lots of news on the resources industry, people and events, must-read articles from our regular contributors, and a great feature article. *Preview* **203** celebrates the end of a very busy and extremely productive year for our Society.

This year has been a significant year of transition for the ASEG's publications as we've worked through the handover from our former publisher, CSIRO Publications, to Taylor & Francis Australia. Our *Preview* Editor, Lisa Worrall, together with Associate Editors, and our *Exploration Geophysics* Editor Mark Lackie, Co-Editors, Associate Editors (and let's not forget our army of dedicated peer reviewers), have delivered six issues of *Preview* and six issues of *Exploration Geophysics* to our Members. Behind the scenes there has been an extraordinary commitment and effort to working very closely with the Taylor & Francis team to establish best lines of communication and to refine the efficiencies and scheduling in our publication workflows so that our Members received these world-class publications on time. There is still further work to be done on this front.

I do see a lot of industry and geoscience society magazines and newsletters and, in my view, nothing comes close to *Preview*'s diversity and depth of exploration geoscience features and articles – in particular, *Geophysics in the surveys; Canberra observed;* book reviews; environmental, mineral and petroleum news and opinions; latest education matters; data trends and specialist updates, such as, global implications of the EU introduction of General Data Protection Regulation (GDPR).

There are real highlights for me in the mix of feature articles over the past six issues of *Preview*. I usually go to the feature article first, and over the year I've really enjoyed "Space rocks on display at Geoscience Australia"; "Mining to Mud: a multidisciplinary approach to understanding Victoria's riverine landscape as a product of historical gold mining"; "The Australian Continent: a geophysical synthesis"; "The second lecturer in exploration geophysics in Australia"; "Perth's lost guns: a geophysical case study"; "A new experimental extractive technology trial for Cooper Basin unconventional resources" and of course, Don Emerson's feature in this issue.

Exploration Geophysics, Vol 50, Issue 6, has recently been published on-line. While I can't claim to have read or browsed the majority of papers in Volume 50, I have found some gems, such as "3D electromagnetic modelling and inversion: a case for open source" by Oldenburg *et al*. While I do miss receiving printed copies of *Exploration Geophysics*, I really appreciate the ease of online reading any ASEG technical paper from Volume 1 – Volume 50.

The first major publication for 2020, the start of ASEG's 50th Year, will be *Exploration Geophysics* Vol 51, Issue 1, a special Airborne Electromagnetics (AEM) issue which has been in the planning for some time by our Editor, Mark Lackie. I very much look forward this new ASEG AEM Volume.

I'm sure I speak for all of our ASEG Members in congratulating our Editors and their teams for their professional time, dedication and commitment in producing such an outstanding body of publications for our Society throughout 2019!

ASEG individual Members have now received the Annual Membership Renewal package via email and will also see the table of 2020 Membership Fees in this issue of *Preview*. Earlier in 2019, the ASEG Federal Executive reviewed the level of fees applied by the other major Australian geoscience societies and confirmed that ASEG fees are comparable. The 2020 ASEG Fees have been increased according to the Consumer Price Index. A generous discount is offered if you renew your membership before Friday, 3 January, 2020.

My very best Christmas and New Year wishes to all ASEG Members around the world, and particularly to our dedicated ASEG volunteers who have achieved so much in 2019.

Ted Tyne
ASEG President
president@aseg.org.au

Renew your ASEG membership before 2020 and save!

The ASEG is acknowledged across the resources industry as a leading and influential professional exploration geoscience society. We draw on an extraordinarily diverse pool of member volunteers to lead and operate the Society, deliver our bi-monthly scientific journal, *Exploration Geophysics*, (continuously over almost 50 years), our premier industry-focused magazine, *Preview*, (continuously over more than 30 years) and the Society's signature International Exploration Geophysics Conference & Exhibition (every 18 months for more than 40 years).

Your membership fee is critical to securing the ASEG's annual programme of publications, state and national technical meetings, conferences and workshops, our Young Professionals initiatives and the work of the ASEG Research Foundation. **Renewing and new Members are offered a generous discount if they pay their fee before Friday, 3 January 2020.**

ASEG membership benefits include:

- *Preview*: stay up to date with current trends in exploration geophysics through the ASEG's bi-monthly magazine.
- *Exploration Geophysics*: access high-quality research results and relevant case studies in the ASEG's technical journal.
- Reduced entry fees for Australian Exploration Geoscience Conferences
- Free entry to monthly technical nights in your state: a wide variety of topical up-to date talks in an informal setting.
- Social events in your state: these include lunches, Christmas events and golf tournaments.
- Access to the annual wine offer: each year, the SA/NT Branch (with recent input from the VIC Branch) curates a selection of local wines for national distribution to members at reduced cost.
- Professional contacts: connect with a generous professional network with wide experience.
- Research funding: student Members may access funding for projects through the Research Foundation.
- Professional growth: mentoring and training opportunities particularly for young professionals
- Access to job advertisements posted on the ASEG's website.
- Opportunities to direct and contribute to the profession by serving on state and federal executive committees.

ASEG membership fee 2020 Individual Membership - Australia	Early Bird Before Friday, 3 January 2020 Incl. GST ($AUD)	Regular After Friday, 3 January 2020 Incl. GST ($AUD)
Active	152.00	175.00
Active 5-year membership	760.00	874.50
Associate	152.00	175.00
Associate 5-year membership	760.00	874.50
Retired	76.00	89.00
Retired 5-year membership	379.50	440.00
Honorary	No Fee	No Fee
Graduate	66.00	76.00
Student	No Fee	No Fee

ASEG Membership fee 2020 Individual Membership – International World Bank 1, 2, 3 and 4 countries*	Regular Excl. GST ($AUD)
Group 1 & 2 (e.g. India, Papua New Guinea, Zambia) Active & Associate	13.30
Group 1 & 2 Active & Associate 5-year membership	66.50
Group 1 & 2 Retired	13.30
Group 1 & 2 Retired 5-year membership	66.50
Group 1 & 2 Student	No fee
Group 3 (e.g. Brazil, Malaysia, South Africa) Active & Associate	69
Group 3 Active & Associate 5-year membership	345
Group 3 Retired	$34.50
Group 3 Retired 5-year membership	$172.50
Group 3 Student	No fee
Group 4 (e.g. Argentina, Canada, China) Active & Associate	159
Group 4 Active & Associate 5-year membership	795
Group 4 Retired	80
Group 4 Retired 5-year membership	400
Group 4 Student	No fee

**See the ASEG website for the full list of countries in each group https://aseg.org.au/members/world-bank-groups-listing*

Please contact the ASEG Secretariat by email: secretary@aseg.org.au or phone: +61 2 94318677 if you need assistance with renewing your 2020 ASEG membership, or with joining the ASEG for the first time.

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 monthly meeting that was held in October 2019. We hope you find these short updates valuable. If there is more you would like to read about on a regular basis please contact Megan on fedsec@aseg.org.au

Finances

The Society's financial position at the end of October 2019:

Year to date income: $ 322 426

Year to date expenditure: $ 289 307

Net Assets: $ 774 064

Membership

At the time of this report, the Society had 951 Members compared to 989 at this time last year.

The renewal process has begun for 2020 membership, so don't forget to renew early and take advantage of the early-bird pricing. We are also offering early-bird discounts on our 5-year membership packages for Active/Associate and retired Members. As always, we are grateful to all our members for their continued support of our organisation.

Membership survey results

Earlier this year we asked you to have your say on the state of the industry and the running of our Society. Thanks to all those Members who participated. The response rate was nearly 25%. Some of the results of the 2019 survey are shown in Figures 1–7.

Megan Nightingale
ASEG Secretary
fedsec@aseg.org.au

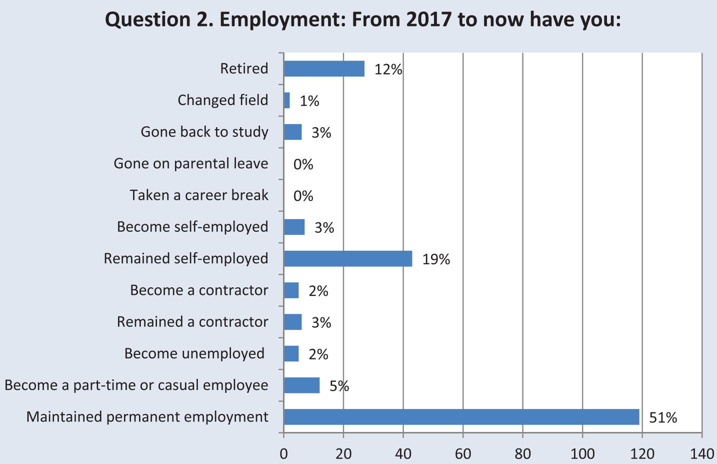


Figure 1. *Member employment status from August 2017 to May 2019.*

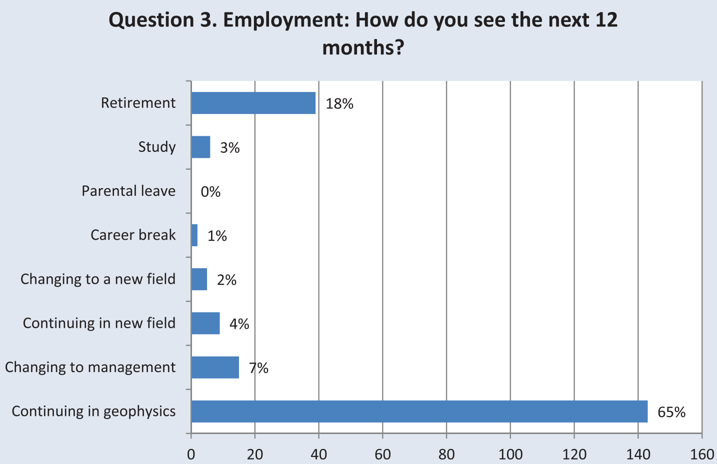


Figure 2. *Member employment plans for May 2019 – May 2020.*

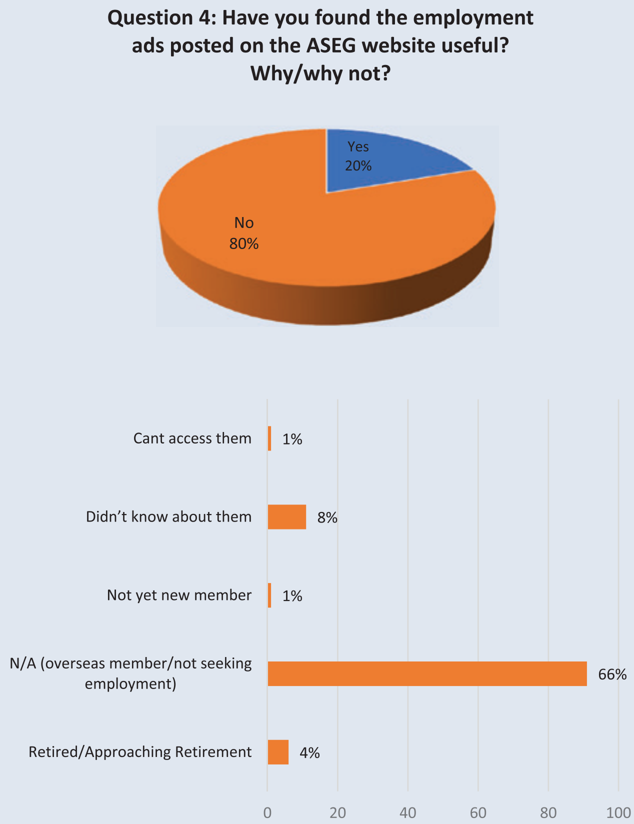


Figure 3. *Usefulness of employment advertising on the ASEG website.*

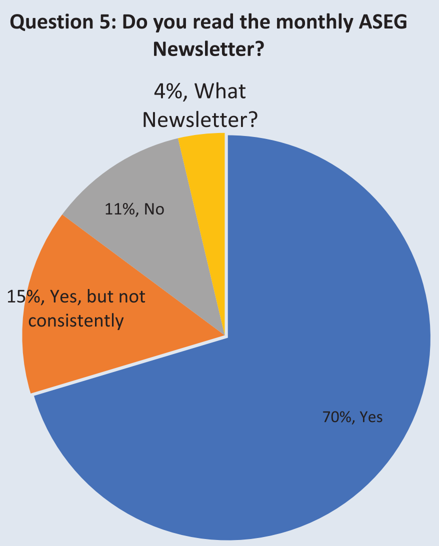


Figure 4. *Readers of the ASEG Newsletter.*

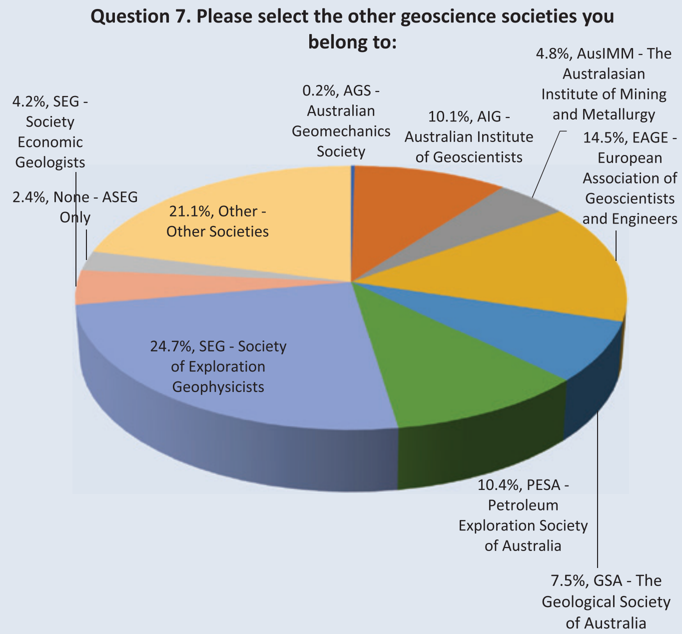


Figure 6. *Other geoscience societies that ASEG Members have joined.*

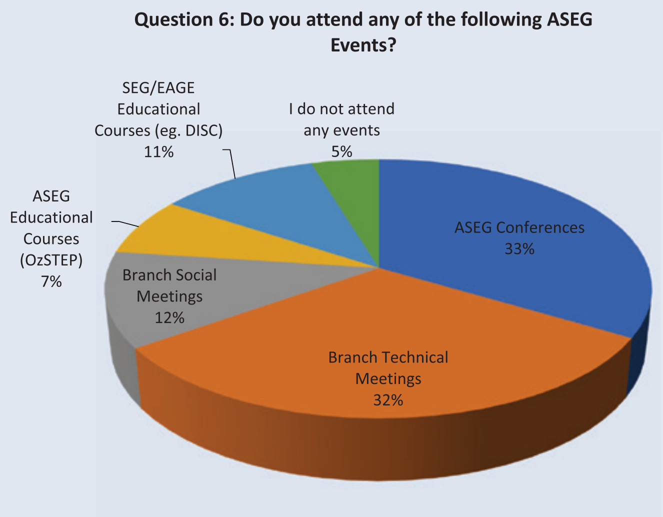


Figure 5. *Member event attendance.*

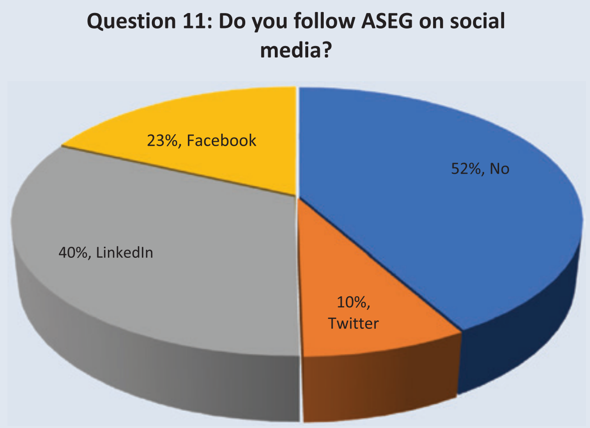


Figure 7. *ASEG social media following.*

Welcome to new Members

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

First name	Last name	Organisation	State	Country	Membership type
Luke	Forti	Kinematex	WA	Australia	Active
Beau	Garland	Macquarie University	NSW	Australia	Student
Rebecca	McGirr	Australian National University	ACT	Australia	Student
Evren	Pakyuz – Charrier	Intrepid Geophysics	VIC	Australia	Active
Nuwan	Suriyaarachchi	University of Western Australia	WA	Australia	Student
Remke	Van Dam	Southern Geoscience Consultants	WA	Australia	Active

ASEG Young Professionals Network: Training, training, training!

One of the biggest challenges for the future of the oil and gas industry is a skills shortage. Have you heard about the reported industry talent crisis? A lack of graduate recruitment during the downturn has been compounded by the age distribution of the industry workforce. According to the 2019 Global Energy Talent Index report (compiled by Airswift and Energy Jobline), nearly one quarter of workers in the oil and gas industry are aged above 55.

This places significant importance on the retainment and ongoing training and development of our Young Professionals (YPs). Consider how long it takes to train and develop staff in the oil and gas industry relative to other industries. Graduate programmes alone will not cover the skills deficit. Even now as the industry continues to recover from the downturn, I am witnessing YPs with 6–10 years' experience leave the industry due to limited job opportunities. I should also mention those graduates that fail to even find opportunities to enter industry.

In an article earlier this year I discussed the scarce technical training opportunities for young professional geologists and geophysicists, especially since the downturn. This article serves as an update on local PESA/ASEG YP activities here in Melbourne to raise awareness of our low-cost training opportunities and to encourage ongoing participation.

We would also like to thank those who have freely provided their time and expertise over the past six months to help bridge the gap in technical knowledge that has been growing over the past several years.

We cannot underestimate the importance for our local industry to invest in the ongoing development of young staff. This is especially relevant for smaller companies without graduate programmes, who often rely heavily on YPs.

This year we have welcomed a wide variety of technical speakers as a part of our PESA/ASEG YP seminar series. Excellent technical presentations have included:

- "Decision quality in the appraisal or when valuing information", Mr Adrian Sikorski
- "2D structural restorations in fold & thrust belts and implications for petroleum systems analysis", Dr David Briguglio
- "A new Full Spectrum FALCON airborne gravity and aeromagnetic survey over the Otway Basin, Victoria", Dr Mark McLean
- "Reservoir characterisation for the next generation" (SEG Virtual Lecture), Dr Subhashis Mallick (University of Wyoming)

Most recently, Angie Cernovskis held a fantastic two-day short course on Petrophysical Interpretation. This is a discipline in which many YPs receive little formal training. Angie has an excellent reputation as a petrophysicist, having worked with Delhi Petroleum, BHP Petroleum and more recently as a consultant based in Melbourne. Well log interpretation is a part of our day-to-day work as geoscientists and petrophysical outputs form a strong component of new ventures evaluation, leads and prospect evaluation, reservoir and seal characterisation and many other areas. We would like to thank Angie for generously providing her time to discuss log interpretation, its pitfalls and workflows.

I remain convinced that upskilling in the current competitive job market is the only way to ensure ongoing employability, with the industry seemingly moving towards more skilled and integrated geoscientists with core skills spread across a wide diversity of disciplines.

PESA/ASEG has several low cost and exciting training opportunities planned over the coming six months, as well as our ongoing technical seminar series. Full fee-paying senior professionals are also welcome to attend these training courses. Please contact either me (dthompson@3doil.com.au) or Jarrod Dunne (jdunne@karoonenergy.com.au) for further information.

We are also looking for industry partners for a Summer Internship Programme in Victoria. If your company would like to express interest in an Internship Programme, please contact Jesse Cotterill (jcotterill@3doil.com.au).

Daniel Thompson
dthompson@3doil.com.au

ASEG Technical Standards Committee: An update

The ASEG Technical Standards Committee met during the AEGC in September in Perth. Fourteen were in attendance (a reasonably pleasing number), with most State jurisdictions represented in addition to several representatives from Geoscience Australia (GA) together with highly experienced industry practitioners Kim Frankcombe, David Pratt and David Allen. The absence of any of the major survey contractors was, however, notable. Mark Duffett chaired, deputising for Tim Keeping.

The topics addressed in the meeting included:

- GA's proposed implementation of netCDF/HDF5 as a standard self-describing encapsulation for a wide range of geophysical data types, including airborne magnetic, radiometric and EM, also MT and passive seismic.
- Implications for gravity data of the GDA2020 dynamic datum advent
- Recognition and acceptance of four well established data standards for passive seismic data from distinct user sub-communities.
- Comprehensive data standards being developed by the MT user community. The committee is content to maintain a watching brief with no direct involvement for the time being.

In this meeting and at a subsequent conference workshop GA (particularly Alex Ip) identified the ASEG Technical Standards Committee as the body to which they are looking to take the lead in developing metadata vocabulary standards surrounding their netCDF implementation. This is a welcome development.

GA personnel took some pains to emphasise that their new format is not intended to supplant either the form in which data is reported to Surveys, or what GA is currently delivering externally. Rather, it is a mode of encapsulation analogous to a zip file that facilitates fast dynamic queries of large data sets and machine-to-machine interaction. In particular they undertook to continue to support established ASEG-defined standards (especially ASEG-GDF2) for the foreseeable future.

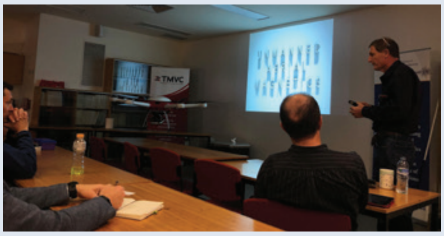
The extent to which the new format is taken up by users outside GA remains to be seen. Support by software developers and vendors will obviously be critical; there is still some way to go in this regard.

Tim Keeping and Mark Duffett
ASEG Technical Standards Committee
technical-standards@aseg.org.au

ASEG Branch news

Tasmania

Tasmania Branch Member **Anton Rada** presented a fascinating overview of the history, present state and possible future of unmanned aerial vehicles (UAVs) or drones for airborne geophysical surveying, at the Tasmania Branch meeting held in the CODES Conference Room on Wednesday October 16. Over 20 Members and students saw how early developments with relatively large aircraft supported by elaborate ground control trucks progressed to smaller and lighter systems, culminating in the several generations of models that Anton has designed and built himself.



Anton Rada presenting to the Tasmanian Branch (photo taken by ***Esmaeil Eshaghi****).*

Examples of the ground clearance, resolution and accuracy obtainable for aeromagnetic work were shown, together with insights into the attendant challenges. One of these being safety considerations (something about cutting-edge technology sprang to mind at this point), rather than a live demonstration we were treated to some video showcases of the technology in action in the field. Not that it's all beer and skittles – the photos of machines that came to grief were reminders that no R&D or innovation comes without setbacks along the way and learning from them.

Drone on display during Anton's presentation (photo taken by Esmaeil Eshaghi).

All ASEG Members, whether Tasmanian or visiting, are invited to get in touch with Mark Duffett taspresident@aseg.org.au or Matt Cracknell tassecretary@aseg.org.au if you'd like a similar opportunity to tell your geophysical story to an enthusiastic audience.

ASEG Members might be interested in the Tasmania Geoscience Forum, which will be held on Thursday 5 December 2019 at the Tidal Waters Resort, St Helens https://ausimm.com/news/registrations-now-open-tasmania-branch-geoscience-forum-2019/

Members might also be interested in an Australian Geomechanics Society workshop on "InSAR and its application for understanding ground movement", which will be held in Hobart 12 – 14 February 2020. This workshop will provide end-users and those commissioning imagery a basic understanding of the technique and its limitations in order to improve success and avoid disappointment. The workshop will be delivered by Dr **Berhard Rabus** (Simon Fraser University), an expert in InSAR technology, and Dr **Nicholas Roberts** (Mineral Resources Tasmania), an experienced InSAR end-user. See details at AGS's website https://australiangeomechanics.org/courses/ags-tasmania-radar-interferometry-workshop/ for registration. Priority will be given to those who have responded to the initial call for interest. However, several additional spots will likely be available.

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. As always, we encourage Members to also keep an eye on the seminar programme at the University of Tasmania / CODES, which routinely includes presentations of a geophysical and computational nature as well as on a broad range of earth sciences topics.

Mark Duffett
taspresident@aseg.org.au

Victoria

The silly season is officially upon us! If you started the year as a geophysicist and if it looks like you'll end 2019 quietly as one, then you are boring. I'm only teasing, you're not boring – you are stubbornly determined. The sort of desirable(?) trait that makes a geophysicist … well, a bloody good geophysicist, I reckon. In any case, congratulations – you've done extremely well in the current challenging environment in helping to prolong your career. Let's all take a moment to remember those geophysicists that became a casualty of 2019 … let the purge continue! LOL. If this got a reaction out of you, then great. Please send any objections or protests in a Letter to the Editor because frankly, the last whinge about being spoilt for choice as to which industry event to attend is clearly a case of being over-entitled. This will keep you busy, Lisa.

Further to our last *Preview* contribution, I regret to inform our readers that Dr **Mark McLean** of the Geological Survey of Victoria (GSV) stubbornly refused to wear our sponsored bear suit on the night of October 1, where we eventually allowed him to proceed to present results from the Victorian Gas Programme, which showcased the latest data from GSV's recently acquired full spectrum FALCON survey over the Otways. This topic managed to drag Dr **Mark Dransfield**, one of Australia's most controversial pioneers of the Australian airborne gravity gradient scene, out of hiding and directly into the fray. Mark (McLean) showed the relatively large audience in attendance that night some pretty interesting colourful images, which would have made fantastic dining place mats.

Our next and final technical night for 2019 was held on November 13. Our guest speaker was **Hammad Tariq**, whose presentation was entitled "Vertical Seismic Profile for reservoir characterisation". If you didn't know anything about VSPs, or wished to learn a little more about it, then hopefully you joined us that night, even if it was just for a drink or to say "hi".

Finally, we end the year with a couple of changes to the make-up of the Branch Committee. **Theo Aravanis** has been deployed as our Treasurer after **Greg Walker**'s recent departure – welcome to the Committee Theo! We also welcome **Mikayla Sambrooks** into the fold as the Victorian Branch's representative on the Communications and Promotions Committee that was recently formed to assist with the ASEG's digital transformation strategy. If you own a phone, and honestly who doesn't, then you should be accessing

ASEG news

the ASEG's social media sites for all the latest and greatest updates.

Please take the time to enjoy yourselves and go crazy during the festive season, not too crazy but crazy enough to consider continuing as practising geophysicists in 2020. Thank you to all our Members for your unwavering support this year, especially for putting up with our antics. You all deserve a pay rise … maybe.

Victorian Branch Meetings are generally held on the third Thursday of each month from 17:30 in the Kelvin Club, 18 – 30 Melbourne Place, Melbourne. Meeting notices, addresses and relevant contact details can be found on the Victorian Branch page of the ASEG website.

Thong Huynh
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Western Australia

On October 9, not long after the AEGC in September, the WA Branch hosted a Tech Night that featured a presentation by **Mark Lindsay**, Senior Research Fellow from CET, on "What is that anomaly? Using machine learning to obtain geological knowledge from downhole petrophysical data". On November 13 **Marianne Rauch** from TGS gave an interesting talk titled "PSDM in relatively benign on-shore settings".

Mark Lindsay presenting to the WA Branch at the Celtic Club

Overall, 2019 has been a good year for the WA Branch with ten Tech Nights featuring SEG HL and SEG DL speakers and a range of presentations from both the mineral and petroleum exploration fields in geophysics. We thank all our presenters in 2019: **Boris Gurevich**, **Don Furseth**, **Wayne Pennington**, **Felix Herrmann**, **Claudia Valenti** and **Alex Costall**, **Darren Hunt**, **Tim Dean**, **Andrew Long**, **Andrew Fitzpatrick**, **Mark Lindsay**, and **Marianne Rauch**.

The Branch also collaborated with PESA WA on a Young Professionals speaker night, and a successful mentoring programme with SPE. 2019 also showcased Perth via the AEGC, which drew a diverse audience of geoscientists across the resources sector.

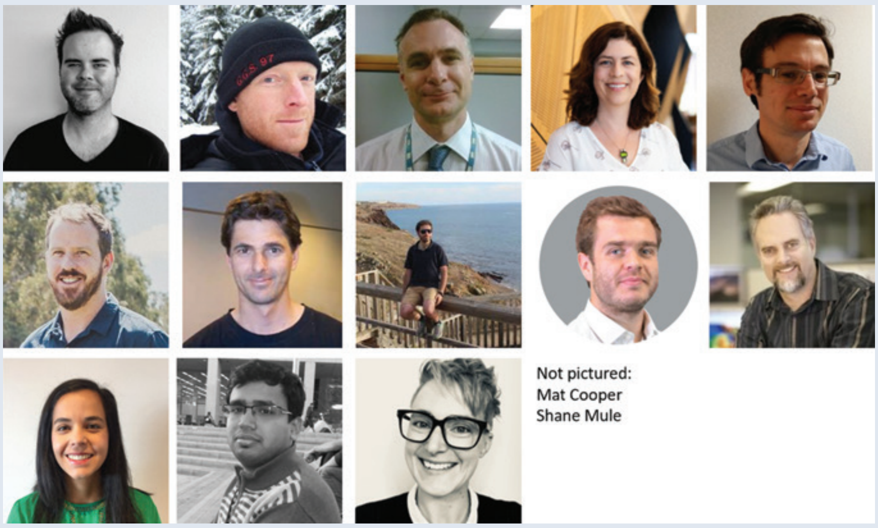
The WA Branch acknowledges and thanks our sponsors for 2019, through their support we are able to host free events for our Members.

2019 WA Branch sponsors, all of whom are gratefully acknowledged

I would like to take this opportunity to welcome and introduce our 2020 WA Branch Committee:

- **Mathew Cooper** (Treasurer)
- **Andrew Fitzpatrick** (Golf Officer)
- **Karen Gigallon**
- **Brett Harris**
- **Luisa Herrmann**
- **Tom Hoskin** (University Officer)
- **Partha Pratim Mandal** (Secretary)

The final message I would like to share with Members in my last report as WA President, is the thanks that I would like to give to the 2019 WA Branch Committee. These individuals have on several occasions gone above and beyond to help contribute to the running of the Society in Perth. Without them the ASEG WA Tech Nights and AEGC 2019 would not have happened. If you see any of them around town, please say thank you.



2019 WA Branch Committee: ***Cameron Adams, Brett Adams, Mark Brailey, Mathew Cooper*** *(Treasurer, not pictured),* ***Jane Cunneen, Tim Dean, Andrew Fitzpatrick*** *(Golf),* ***Brett Harris, Amir Hashempour Charkhi, Alexander Karvelas, Shane Mule*** *(not pictured),* ***Matt Owers*** *(Secretary),* ***Carolina Pimentel*** *(Mentorship / YP),* ***Partha Pratim Mandal****, and* ***Heather Tompkins*** *(President).*

On behalf of everyone on the WA Branch Committee we would like to wish all our Members a safe, healthy, and happy holiday season.

Heather Tompkins
wapresident@aseg.org.au

Australian Capital Territory

The ACT Branch is proud to announce the successful applicant for the first Dr **Peter Milligan** Student Award. The successful applicant was **Rebecca McGirr**. The selection panel had a hard time as Rebecca was one of a number of applicants who showed a wide array of skills and accomplishments. Rebecca will give a presentation of her work at a date to be determined.

On October 9 **Clive Foss** gave a talk titled "The enigmatic 'pimple' magnetic anomalies of the Eucla Basin". Clive gave examples how some anomalies are so small they only appear on single lines, even when the line spacing was 200 m, and were thought to align with limestone fractures.

On October 14 the Branch was fortunate enough to have presentations from two United States Geological Survey representatives. The talks covered the use of AEM for regional groundwater studies in the Mississippi Alluvial Plain, and National-scale magnetotellurics. Both of these talks covered topics similar to current Geoscience Australia programmes, and it was good to hear how other countries are dealing similar issues.

On November 12 **David Pratt** gave talk titled "A new magnetic tensor approach to mapping magnetic rock properties and cover depth using AI" – a very interesting topic.

The ACT Branch is looking forward to our Christmas party on November 28. The party will be preceded by a technical talk.

Phillip Wynne
actsecretary@aseg.org.au

New South Wales

In September, **David Pratt** (Tensor Research) spoke about "A new approach to mapping magnetic rock properties and cover depth using AI". The presentation covered the use of an expert system AI method applied to magnetic data for mapping depth of cover and formation properties as a constrained 3D geological problem. Dave emphasised that with recent developments in the acquisition of magnetic data having resulted in high resolution magnetic data, it now means that it is possible to get improved estimation of magnetic susceptibility via AI methods. Dave walked us through a couple of examples to emphasise how the AI approach would be utilised. There were many questions and much discussion.

Dave Pratt holding his thank-you gift for presenting to the NSW Branch

In October, **Cameron Fink** (Bridgeport Energy) gave a presentation on "Moonie Oilfield – then, now and into the future". Cam went through the discovery and development of the field and worked his way through the evolution of the field. Cam noted that with a naturally occurring active water drive via the Precipice sandstone, secondary recovery (water flood) has effectively already taken place. In order to extract more oil, a CO_2-miscible flood Enhanced Oil Recovery (CO_2-EOR), could be implemented. Cam outlined Bridgeport Energy's vision is to proceed with a CO_2-EOR project to both liberate an estimated additional 8-10 million barrels of oil from the subsurface, and to simultaneously respond to the climate-aware public's cry for a mechanism to reduce CO_2 in our atmosphere. Cam emphasised that we may well be on the cusp of this so-called "Green Oil" revolution in Australia.

*Bridgeport Energy employees supporting Cam after his presentation on Moonie. Left to right: **Steph Kovach** (ASEG NSW Branch Secretary), **Sherwyn Lye** (former ASEG NSW Branch Secretary), **Nancy** and **Cameron Fink** (Bridgeport Energy).*

The NSW Branch of the ASEG was a bronze sponsor for GESSS (Geological Society of Australia Earth Science Student Symposium) NSW 2019 – a conference organised by students for students. In its third year, GESSS NSW was held at UNSW between 31 October and 1 November and the NSW Branch Secretary (Steph Kovach) had the pleasure of attending on Friday morning. The student presentations were extremely interesting, ranging from reconstruction of the Sydney Basin, to rocks revealing

*GESSS NSW 2019. Left to right: **Stuart Clark** (UNSW & ASEG NSW Branch Committee member), **Liz Dowding** (GESSS-2019 Chair and UNSW) and Steph Kovach (ASEG NSW Branch Secretary).*

the subduction trends in the NW Yilgarn. After morning tea, a presentation by **Peter Betts** (Geological Society of Australia) examined the importance of geoscience to society, and how as geoscientists we need to change the narrative of how we communicate the importance of our work. The panel discussion that followed was entitled "Mapping the future of Earth Science: diversity of practice and practitioners". GESSS NSW 2019 was a well organised event and the NSW Branch was proud to be a sponsor.

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

Mark Lackie,
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Stephanie Kovach
nswsecretary@aseg.org.au

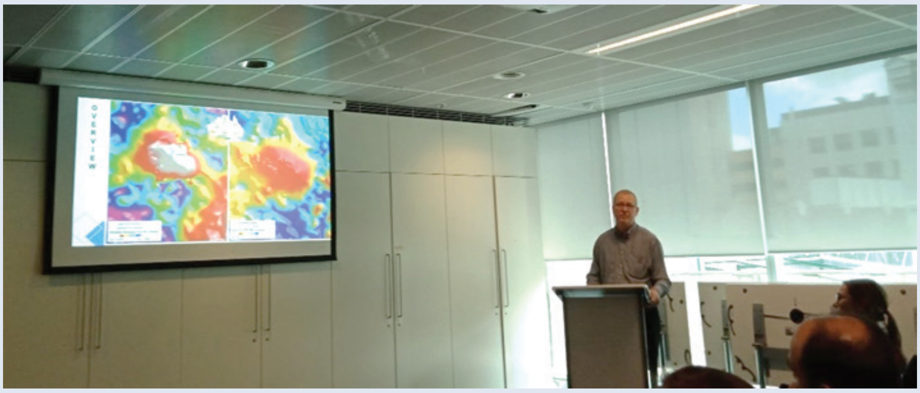
Queensland

Dr **Sasha Aivazpourporgou** gave a talk to the ASEG Queensland Branch on August 29 entitled "Lithospheric structures of the Newer Volcanics Province, western Victoria, Australia from a long-period magnetotelluric array", which was well attended. Sasha gave a few examples of her work and experience with MT, and the evening was well regarded and appreciated.

On October 4, and as reported in *Education Matters* in this issue of *Preview*, Gap Geophysics Pty Ltd welcomed students from the Queensland University of Technology and University of Queensland and hosted a half-day tour of their facilities at West End as well as displaying their innovative survey equipment. The visit was insightful and educative in illustrating GAP's latest innovations. ASEG thanks GAP for hosting the visit and commend them for giving their time to students of our profession.

The 2019 mentorship programme wraps up with its final event on November 22, and we would like to thank **Janelle Simpson** for all her hard work. Plans are already underway for a bigger programme next year.

On December 5 the QLD ASEG will be holding a joint Christmas Drinks event with PESA, SPE, QUPEX and FESQ at the Jade Buddha in Brisbane. Follow this URL to register your interest: https://reg.eventgate.com.au/Event/17615/2019-Combined-Oil-and-Gas-Christmas-Drinks



Laz Katona presenting to the ASEG SA-NT Branch

Ron Palmer
qldpresident@aseg.org.au

South Australia & Northern Territory

December already! We have had a busy few months. **Laz Katona** from the Geological Survey of South Australia (GSSA) gave a great lunchtime presentation, co-hosted by GSSA, on October 10. The talk entitled, "Which anomaly should I drill? Using spatial statistics to inform exploration in covered IOCG terranes", was well received and lead to lively discussions.

On October 22 we co-hosted our second (hopefully annual) Spring Fling event with PESA, SPE and Young Petroleum Professionals on a warm evening at the Havelock Hotel. We also took expressions of interest for the 2020 Mentoring Programme. Please let me know if you would like to be involved in the mentoring programme for 2020.

The Spring Fling event in full swing

On November 5 we hosted the 32nd Annual Melbourne Cup Luncheon sponsored by Terrex and Vintage Energy at the Gallery Hotel on Waymouth St. Although I was unable to attend, reports were that a fun day was had by all.

We couldn't host these fantastic events without the valued support of our sponsors. We heard the exciting work that some of our sponsors have been up to at our Annual Industry Night at the Coopers Alehouse on November 14. The SA-NT branch is sponsored by Beach Energy, Heathgate Resources, Vintage Energy, Geosensor, Department for Energy and Mining, Terrex and Zonge.

Our Committee member and Branch Secretary **Ben Kay** has been busy finalising the wine offer which was another great success, and hopefully you have all received your wine by now (at the time of writing I'm eagerly awaiting my sparkling wine!)

On November 8 I attended the GESSS SA 2019 student symposium, of which SS-NT Branch of the ASEG was a proud sponsor and the donor of a monetary prize to the best geophysics presentation. Judging was a tricky task because although the number of geophysics presentations were few, the quality was high. Congratulations to **Michael Curtis**, a PhD student at ASP at the University of Adelaide for receiving the award for his excellent presentation on the perils of igneous rocks in petroleum exploration, and his efforts to map their locations.

To end the year off we have our annual student honours night and Christmas party on December 12, which is sure to be an enjoyable evening! I will be heading overseas for a few months at the beginning of December so unfortunately cannot make it, but I look forward to seeing everyone in 2020 and wish all our Branch Members a Merry Christmas and a Happy New Year.

Kate Robertson
sa-ntpresident@aseg.org.au

ASEG national calendar

Date	Branch	Event	Presenter	Time	Venue
Nov	WA	Annual Student Presentation Night	Various	17:30	TBA
28 Nov	ACT	Christmas party and Tech talk	TBA	17:00	Geoscience Australia, Symonston & Rubicon, Griffith, Canberra
29 Nov	SA-NT	SAEMC	Various		Adelaide Convention Centre, Adelaide
05 Dec	TAS	Tasmania Geoscience Forum	Various	09:00	Tidal Waters Resort, 1 Quail St, St Helens
05 Dec	QLD	Christmas drinks		16:00	Jade Buddha, 14/1 Eagle St, Brisbane
06 Dec	WA	ASEG-PESA WA 32nd Annual Golf Classic		08:30	Joondalup Resort, Country Club Boulevard, Connolly
08 Dec	SA-NT	Geofamily Christmas in the Park		10:00	Point Malcolm Reserve, 343 Military Road, Semaphore
11 Dec	NSW	Quiz night	Various	17:30	99 on York Club, 99 York St, Sydney
12 Dec	SA-NT	Mentor wrap-up, Honours night and Christmas party	Various		Hotel Richmond, Adelaide
Dec	WA	AGM and Christmas party	Various	TBA	TBA
12-14 Feb	TAS	GMS InSAR Workshop	Berhard Rabus and Nick Roberts	09:00	Hobart
21	WA	GSWA Open Day	Various	08:30	Esplanade Hotel, Fremantle

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

Henderson byte: Galvani and Volta

Recently I was in Bologna, Italy, the home of Luigi Galvani (1737–1798) who was a pioneer of "animal electricity". A statue in Luigi Galvani square shows him holding a plate on which there is a frog. In 1780 Galvani observed that frogs' legs twitched and retracted when two probes of different metals were applied across them to form a circuit. He attributed this to a new phenomenon, which has been called "bioelectricity" or, more recently, "electrophysiology", a field that today still studies the electrical patterns and signals from tissues such as the nerves and muscles. Along with his contemporaries, Galvani regarded the activation of muscles as being generated by an electrical fluid that is carried to the muscles by the nerves.

Onto this scene came Alessandro Volta (1745–1827) a professor of experimental physics in the University of Pavia, near Milan. At first Volta embraced the theory of animal electricity. However, he began to doubt that the contractions were caused by a specific electricity intrinsic to animals' legs or other body parts. Rather, he believed that the contractions depended on the two-metal cable Galvani used to connect the nerves and muscles in his experiments.

Volta demonstrated that when two different metals are separated by a brine-soaked cloth they produce an electric current chemically. He realised that the frog's legs merely served as a conductor of electricity, or what we would now call an electrolyte. Such a configuration is called a "galvanic cell" (*sic*), or "voltaic cell".

In 1799 Volta stacked several pairs of voltaic cells together through which an electric current flowed in what became known as "voltaic pile" (the French word for battery is "pile"). Thus, Volta had invented the first battery, which he then used to disprove Galvani's theory of electricity being intrinsic to animals.

The requirement that the metal electrodes be of different metals is a recognition of their different electrical potentials. The amount of difference is the electromotive force, or emf, of the cell. It is after Volta that the SI unit of electric potential is named as the volt (V).

Galvani's name is not used officially for a standard unit in physics, however it has provided us with the verb "to galvanise", meaning to stimulate or energise.

Roger Henderson
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Vale: Dr Barry Drummond (1950–2019)

Dr Barry Drummond

Sadly, the Australian geoscience community has lost a wonderful person after a short illness. For those of you who knew Barry, I think there can be no doubt in your minds that he was a great leader and mentor to many. His contributions to Australian earth science were considerable, and were across a broad spectrum of geoscience. He will be truly missed by the many colleagues he was associated with over the four decades of his professional career, and those he continued to work with during his retirement.

Many of us benefited enormously from Barry's guidance and wisdom in supporting our own careers as we developed as scientists, managers, technicians and leaders. He always endeavoured to encourage us to develop solutions to whatever problems we faced by giving us the confidence in our own knowledge, skills and abilities. In turn, he taught us to treat our staff in the same way, something which I hope has imparted an enduring legacy. When we went off in the wrong direction, he would always strive to help us understand how an alternative path might be a more sensible way to proceed. I think that Barry also benefited from the mentorship he received from others who were pioneers in Australian geoscience, Jim Dooley for example, Professor Anton Hales and Dr John Cleary.

We are fortunate that after his retirement from Geoscience Australia in 2011 Barry was able to record some key moments in his career. His records, along with contributions from some of his former colleagues, have allowed me to share many of his great contributions and achievements to Australian geoscience with *Preview* readers.

Barry's interest in the earth sciences was fostered at an early age by his grandfather, who was a coal miner and fossicker for precious and semi-precious stones. At the age of 11 his uncle took him down a coal mine which he found a fascinating experience. The scene was thus set for fifty plus years in geoscience!

Barry had a good aptitude for maths and physics in high school, which combined with his interest in rocks led to a leaning towards geophysics. He was further attracted to geophysics by the father of a school friend who managed a geophysical contracting company in his home town of Toowoomba. At that time the Moonie oil fields were being discovered and south-west Queensland was the centre of oil exploration in Australia. Geophysics thus offered a career in interesting subject matter that was aligned with his academic strengths and with opportunities to work outdoors.

After he completed a Bachelor of Applied Science degree majoring in geophysics at the University of Queensland (UQ) in 1971, he gained a position as a cadet geophysicist with the Bureau of Mineral Resources (BMR). Barry and his wife Linda moved to Canberra in 1972, where his early years were spent working on seismic refraction surveys designed to measure the thickness of the Earth's crust. These surveys included the Trans Australia Seismic Survey (1972); the Bowen Basin Refraction Seismic Survey, which commenced his long-term collaboration with Clive Collins who was then at UQ; and the 1973 East Papua Crustal Survey (EPCS). In his first years at BMR he was involved with the development of analogue seismic recording and playback systems for crustal refraction surveys that were first tested in the trying conditions encountered in PNG. EPSC was a collaborative activity between six tertiary institutions, four government departments and eight contractors. This "herding cats" experience obviously put him in good stead for the rest of his career in negotiating with a diverse range of stakeholders across numerous sectors. This combined with the work he undertook into understanding the Earth's crustal structure certainly influenced a large part of his future career.

The 1977 Pilbara Crustal Survey led to Barry gaining the support of a Public Service scholarship to undertake an MSc at the ANU, which he submitted in 1979. This was immediately followed by his PhD study titled "Crustal evolution in northwest Australia – evidence from seismic refraction data", based on deep crustal seismic refraction profiles using quarry blasts and the odd 10 tonne explosive shot detonated by Barry's BMR crew. After completing his PhD studies Barry started to combine the refraction results from deep seismic reflection surveys with which the BMR had been experimenting since the mid-1950s, and had been routinely acquiring along long regional reflection seismic lines from the early 1980s.

In 1987 Barry was given the task of integrating the BMR seismic reflection and seismic refraction programmes, and increasing their relevance to other parts of the BMR programme at that time. This presented a significant challenge as he needed to overcome resistance from those who wished to keep reflection seismology in the petroleum silo and, with no previous management experience, he had to manage a couple of dozen scientists and technicians who were reluctant to change. This was both a

significant point in Barry's career and, in fact, the driver for him to undertake deep crustal reflection seismic surveys in hard rock terranes. Twenty plus years later the value of this work to understanding fluid pathways for mineral systems is well demonstrated through discoveries such as the Wallaby and Gruyere gold deposits in the Yilgarn Craton. Senior management in BMR also recognised that Barry could take on difficult tasks, and be successful in delivering complex programs.

In 1990 Barry was a key driver in the ACORP (Australian Continental Reflection Profiling) programme. This initiative brought together key earth imaging people from academia, government and industry to plan an ambitious programme of deep seismic transects across the continent to address key geological questions on the 3D structure of the Australian crust. Over the last thirty years or so essentially all of these transects, and more, have been acquired with the result that that Australia probably has the most extensive onshore deep seismic reflection coverage in the world. At around the same time Barry edited the Geological Society of Australia volume *The Australian Lithosphere*, which was a selection of papers from various geo-disciplines integrating the knowledge of the lithosphere at the time to enhance the understanding of its properties.

In 1991, under Barry's leadership, the BMR took seismic reflection profiling into a minerals area in earnest. The Eastern Goldfields seismic survey results subsequently changed the prevailing views of greenstone evolution and mineral system formation. It also fundamentally changed the way that BMR worked, as it was a turning point in the understanding of mineral systems and the power of seismic reflection to image large scale systems and fluid pathways, although it took well over a decade for this to be truly recognised in the geoscience community.

The success of BMR's, then AGSO's (the Australian Geological Survey Organisation) seismic programmes in the late 1980s and early 1990s led to AGSO being invited to join a bid for funding for the Australian Geodynamics Cooperative Research Centre (AGCRC) with the seismic programme as its lead in science under the leadership of Barry. This resulted in a number of new and innovative experiments such as the 1994 Mt Isa Project, which took a multidisciplinary approach involving seismic reflection, seismic refraction, potential fields, geology, geochemistry and regolith studies. In addition, this AGCRC project brought together researchers from several universities, CSIRO and exploration companies. The quantum of development in understanding of fluids within the basement and their migration by linking seismic architecture, chemical modelling and crustal deformation was world-leading at the time, and was pioneering in the application of earth imaging to mineral system targeting. The success of the AGCRC led to the establishment of the Predictive Mineral Discovery CRC (PMDCRC) in 2001, and Barry provided scientific direction for several seismic surveys, with significant surveys being conducted in the Gawler and Curnamona Cratons. These surveys provided new insights to whole-of-crust structures in the Olympic Dam region.

In 1995 the French Government resumed nuclear weapons testing at Mururoa Atoll in the Pacific Ocean. The Minister for the Environment formed an expert panel of scientists to advise on the potential effects on the region, and Barry was invited to participate. He learned a number of things about advising the Government from this experience. Firstly, scientists may have the answers to many important questions but are often excluded from discussions when the topics become controversial. Secondly, not all scientists will share the same view. Those who deal with sensitive material regularly will often not understand the perception of risk in other people's eyes. It also became apparent that few people, apart from geoscientists, understood the concept of time. Mururoa Atoll contains a lot of radioactive material that will probably leach out through natural systems over time. Sadly, the message that this will not be a nice place to visit will be lost over time. This story is also very pertinent to the problems humanity faces in the 21st century.

Also, in 1995, under Barry's leadership, AGSO in conjunction with Mineral Resources Tasmania (MRT) and the AGCRC commenced a major study to create a 3D model of the Tasmanian lithosphere. This project, TASGO, ran for a number of years and resulted in a number of innovative developments that combined multidisciplinary geoscience datasets into a 3D VRML visualisation for the whole of Tasmania, providing several new insights into the evolution and structure of the Tasmanian crust.

Then, partway way through the AGCRC and whilst the TASGO project was in full swing, an opportunity arose to write an application to set up a Major National Research Facility (MNRF) in seismic imaging. Barry, in collaboration with Professor Brian Kennett at the Australian National University, was successful in obtaining over $5M in funding to set up the Australian National Seismic Imaging (ANSIR) MNRF. As the inaugural Director of the Facility Barry oversaw the procurement of state-of-the-art seismic reflection equipment and a pool of broad-band seismic instruments. ANSIR equipment then provided the infrastructure that would allow researchers to image the Australian lithosphere at multiple scales and resolution. It is a testament to Barry and Brian's leadership that twenty plus years later ANSIR has grown and evolved with new equipment and techniques, and continues to support earth scientists interested in imaging the Earth. The research paradigm developed within ANSIR encouraged scientists to codify hypotheses about structure, depth and formation, and then use seismic imaging techniques to test their hypotheses. This was not the traditional way to undertake many geological studies and very few of the hypotheses fully withstood the test of the seismic images, leading a former GA CEO to call ANSIR "The Truth Machine".

During his time as Director of ANSIR Barry maintained his research focus on mapping fluids in the crust, working closely with colleagues at CSIRO. He used CSIRO software to predict the behaviour of fluids in the crust, and then examined seismic images for evidence to test the predictions. A geologist working for a multinational gold company wrote in a letter of support for a submission for funding for ANSIR that work to date (coupled with work by his company) had contributed to the discovery of an estimated $3 B of gold in the ground. In a classic seismic image from subsequent research, fluid pathways emerging from the mantle can be traced through strata in the crust and eventually seen to reach the upper crust where they formed the gold deposits near Laverton in Western Australia. Similar structures could be seen in seismic data in an area in the desert farther to the east in the Yarmana Belt, where the 6.6M oz Gruyere deposit has

subsequently been developed with its first gold production in 2019.

Barry concluded his term as ANSIR Director in 2003, and Brian Kennett took over as Director. At this time Barry was managing GA's airborne geophysics programme, its gravity programme, its national geological maps project, a programme looking at new innovations in geophysics and how they might be applied in the minerals industry, and the development of GA's national geological databases.

These were all exciting projects, and all linked in ways that would ultimately allow for the development of new Australia-wide geological and geophysical maps that could be used for a wide range of applications. Mineral and petroleum exploration are obvious examples, but there are many others. A visiting ecologist once asked why GA had a map of the distribution of various ecologies in north Queensland where he was undertaking research. This was a geological map that demonstrated that geology controlled soil type and landform and that they, in turn, were influencing the distribution and types of natural habitats.

During this time GA completed the first-pass airborne magnetic map of Australia. It had taken 40 years. It has proven to be a very valuable map for a number of reasons, and shows the importance of the work of geological surveys that have the resources, charter and tenacity to continue very long-term scientific programmes. Understanding this was important for Barry, as later in his career he was given oversight of the national geodetic programme.

As with many things in the course of a career, events occur which alter one's direction, often in a very dramatic way. The earthquake that occurred in the sea off Aceh Province in Indonesia on December 26, 2004, and generated a tsunami that claimed over 230 000 lives, marked another major turning point in Barry's career. Prime Minister Howard stated within days of the disaster that Australia would contribute to the development of an Indian Ocean Tsunami Warning System. Funding was allocated in the Federal budget in May 2005, after a lot of lead up work by teams of people at GA, the Bureau of Meteorology, and Emergency Management Australia. By then the focus of the Australian Government had broadened from the Indian Ocean Tsunami Warning System to include an Australian Tsunami Warning System (ATWS), because it was realised Australia had been impacted by tsunami in the past, including the tsunami in 2004, but Australia had no warning system.

A warning system is different from a warning centre. A warning centre's job is to identify earthquakes that can cause tsunami, look at data from sensors in the ocean to see if a tsunami has been generated, and issue a warning to communities that might be exposed to the tsunami. A tsunami warning system includes not only a warning centre but also undertakes the work needed to underpin advice to communities on how to respond should warnings be issued, and develops and practises evacuation plans. Warning systems also incorporate the recovery phases after a tsunami has occurred.

Barry was tasked with leading the development of the GA part of the warning system. GA's responsibility was two-fold. One was to develop the part of the warning centre that would identify earthquakes with the potential to cause tsunamis that would impact Australia and Australian interests overseas. In effect, because Australians are great travellers, this meant that it had to be able to detect any earthquake over a magnitude 6.5 near a coastline anywhere in the world. GA would then advise the Bureau of Meteorology and the Attorney General's Department, and these agencies would use the communication networks already in place for weather and other warnings to issue tsunami warnings.

GA was given four years to achieve this task, with progress reports delivered to the Prime Minister's Department every three months, and summary reports made available to Federal Cabinet. GA's part of the warning centre was operational after two years using data from the existing seismograph stations that were part of the Australian National Seismograph Network, and data telemetered from overseas stations. At the same time the Australian National Seismograph Network was systematically upgraded and was fully operationalised on schedule in four years.

"Operationalised" meant the system could not fail. This required redundant seismograph stations, data communication systems and computer systems to mitigate against all types of failures. This also required ensuring the various systems, such as the communication systems, were truly independent to ensure 24/7 robustness of the ATWS. Barry was also responsible for delivering the science that underpins the development of sustainable communities and informs the preparation, response and recovery phases of warning systems in Australia and the Australian region.

While Barry was developing the GA component of the ATWS he also had oversight of the national geodetic programme, the national geomagnetic programme, a major part of Australia's nuclear monitoring programme, a project strengthening Papua New Guinea's volcanic monitoring program, and he was responsible for upgrading Australia's earthquake risk map. Each of these were all very interesting and important activities that included international dimensions.

Barry realised that the national geodetic programme was immensely important but was extremely under-resourced. This programme had arrived when AusLIG and AGSO were merged to form GA. The nation needed to modernise its geodetic programme and develop national geospatial reference systems. These are the coordinate systems we use to measure where we are, and the mathematical tools that we use to link the measurement to a location. Such systems underpin a great deal of the nation's economic activity, and are fundamental in the operation of global satellite navigation systems. Additionally, the Australian continent is moving north by around 7 cm each year and the system needs to account for this movement to maintain accurate positioning over time.

During Barry's tenure GA was able to access large amounts of infrastructure money to upgrade the geodetic measuring systems in the country, and the geodetic team was able to improve the accuracy of the reference system by an order of magnitude. In another few decades they are likely to be able to make better estimates of the 7 cm drift by allowing for the internal deformation of the continent. This is long term science that has to have a well-founded business case, and a hosting agency that has the resolve to continue with a task that might span the careers of several generations.

After retiring from GA in 2011 Barry consulted on seismicity induced by hydro-fracturing such as used in the development of coal seam gas, shale gas and oil and enhanced geothermal

energy. In a sense it was a return to work he had done earlier in his career as it is a process that is caused naturally by fluids moving through the earth, demonstrating that the fundamentals of science can be used in a number of ways. He was also in the process of completing some papers on Tasmanian crustal structure, and crustal fluid flow studies in the Yilgarn based on seismic profiling.

Barry has left a significant legacy in all of the areas he worked with over his long and distinguished career at BMR/AGSO/GA and through his retirement years, and in the relationships he built with a broad range of stakeholders in government, academia, industry and internationally. Those of us who have had the pleasure to work with Barry over the years have had our own careers enriched by his insightful guidance, and hopefully we have been able to pass some of his wisdom onto others.

We extend our deepest sympathy for their loss to Barry's wife Linda and his daughters Jean, Kate and Jessica

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Bottom right - Seismic play back East Papua Curstal Survey 1973 (Clive Collins), bottom left - Lachlan Fold Belt seismic reflection survey 1976 (Clive Collins), middle right - Pilbara Crustal Survey 1977 (Clive Collins), middle left - AGSO Canberra 1991 (with Clive Collins) , top right - Canada 2004, top left - GA Canberra 2011 (with Attorney General).

Vale: Dr Sheldon Breiner (1936–2019)

Dr Sheldon Breiner

Australian geophysicists are perhaps not so familiar with the many and often unusual achievements of Dr Sheldon Breiner, a resident of California. However, many know of Geometrics, the Californian company that he founded in 1969 and which has been operating for 50 years.

Sheldon died at the age of 82 at his home in Portola Valley, California, near Palo Alto.

Sheldon began working with magnetometers long before he finished his education at Stanford University where he gained an MSc in 1962 and a PhD in 1967. He was so proficient with them that Varian Associates, a Silicon Valley company that made electromagnetic equipment, employed him while he was completing his master's degree. He is thought to be the first to use optically-pumped magnetometers for geophysics, and part of his research included the first airborne test of a rubidium magnetometer-gradiometer in Arizona. He was also the first to make use of Euler's theorem for depth to magnetic basement determinations as expounded in his MSc.

Taking a slightly different tack, his PhD involved the use of magnetometers to measure the piezo-magnetic properties of rocks under stress as a way of predicting earthquakes. This was inspired by his proximity to the San Andreas Fault and its associated tremors. Indeed, because his home in Portola Valley is on the fault, he maintained a seismograph in his basement as a warning of impending quakes.

While at Stanford, Sheldon met Phyllis Farrington, whose friends know her as Mimi. They married in 1962. In addition to her he is survived by their daughter Michelle, their son David, and five grandchildren. Another son, Aaron, died in 1966.

In 1969, after six years at Varian, Sheldon started up Geometrics and guided its expansion from solely a manufacturer of magnetometers to adding an extensive line of seismographs and geoelectrical instruments as the company matured. The original founding employees were: William Jacobson, Tony McBride, Doug O'Brien, Alan Edberg and Robert Prindle. All but Jacobson had been employees of Varian.

Sheldon promoted the use of magnetometer gradiometers for minerals and hydrocarbons, but the instrument also proved to be efficient at detecting small magnetic objects such as guns. We can thank Sheldon and his magnetometer gradiometers for our security delays at airports and official buildings. Another one of his unique ideas was the insertion of magnets in ski boots to aid in the recovery of victims of an avalanche. In this way, he outfitted the first American team to ascend Mt Everest in 1962.

Sheldon helped the US Government track down sunken submarines, and on one occasion he found a hydrogen bomb that had fallen into the ocean after a B-52 bomber collided with a refuelling jet over Spain in 1966.

He continued leading Geometrics until 1983, when he made the first of his several departures from magnetics and founded Syntelligence Inc., an artificial intelligence company that designed software intended to replicate the wisdom of experts in fields like banking or insurance underwriting. Sheldon also founded a number of ventures specializing in start-up high-tech concerns, only some of which involved geophysics. One such venture developed a resistivity technique for detecting oil through casing, and another aimed to directly detect hydrocarbons from aircraft and deep-towed marine sensors. He was also working on using semiconductor technology, for which he held a patent, to mitigate the consequences of using a mobile phone while driving and, most recently, he was working on an electronic signature verification system. His ideas were always forward-thinking, and he has been described as a serial inventor with many other patents pending.

Sheldon was a prolific writer. He published over 30 technical papers and one book, *Applications Manual for Portable Magnetometers*. Over many hundred thousand copies later, that book is still a primer on the magnetic search for buried objects, the applications of portable gradiometers, operational considerations of proton magnetometers, and the earth's magnetic field and its variations. He was the Heiland Lecturer at Colorado School of Mines, and an occasional lecturer in the Graduate School of Business and the Department of Geophysics at Stanford University. He was a Member of SEG, EAGE, Society of Petroleum Engineers, American

Geophysical Union and various Stanford and local community associations.

In what he must have thought was fun, and a break from the world of corporate business, Sheldon used his personal expertise with more sensitive rubidium magnetometers to help archaeological expeditions around the world. For example, he joined researchers looking for the wreckage of galleons off the coasts of California and Mexico, and he helped discover buried ruins that many archaeologists believe were part of Sybaris, an ancient city in Calabria, southern Italy.

In 1968, on an expedition to San Lorenzo Tenochtitlan, a group of archaeological sites in southern Mexico, Sheldon discovered scores of ancient artefacts, including two enormous basalt heads, one of which weighed about 10 tons. They were made during the Olmec civilization, which thrived as early as 1200 BCE.

Sheldon was an "explorationist" in the way that we geophysicists know the term, but he was also an "explorer" in the sense of a first-time discoverer. Indeed, because of his many explorations, he was, by invitation, a Fellow of the Explorers Club of New York.

His physical fitness as a participator in marathons was apparent to me when I was with him on a business trip to Wellington, New Zealand. Knowing it to be his first time in that city I thought I would show him the sights but he said it was not necessary as he had run the entire perimeter of Wellington Harbour before he had breakfast.

See also another obituary in the prestigious *New York Times* of 1 November 2019 https://www.nytimes.com/2019/11/01/science/sheldon-breiner-dead.html and a 7 plus page article in the *Leading Edge* of April 1984 titled "Sheldon Breiner, Merlin of Magnetics".

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ANSIR NATIONAL RESEARCH FACILITY FOR EARTH SOUNDING

The Australian National Seismic Imaging Resource (ANSIR) was originally created as a Major National Research Facility in 1997 by Barry Drummond from Geoscience Australia and Brian Kennett from The Australian National University to encourage and assist world-class research and education in the field of seismic imaging. Barry, who sadly passed away this year, was the inaugural Director (Editor's note: Barry Drummond's obituary is published in this issue of *Preview*). In 2008, The University of Adelaide joined with support for electromagnetic research, and ANSIR was rebranded to being the National Research Facility for Earth Sounding.

Since 2007 ANSIR has operated in conjunction with the Earth Imaging component of the AuScope facility established under the Government NCRIS scheme. From 2011 AuScope funding from the AGOS EIF programme has provided additional equipment. ANSIR has also received equipment investment from the University sector, ARC and State and Federal Geological Surveys over the years.

The primary role of ANSIR is to act as a national facilitator of equipment, software, training and data for all areas of Earth Sounding. It operates on a scientific community model, with members from ten institutions constituting a Steering Committee. Currently, our membership comprises ANU, CSIRO, Geoscience Australia, Macquarie University, University of Adelaide, University of Auckland, University of Melbourne, University of Tasmania, University of Western Australia and Victoria University of Wellington, but additional members are welcome!

Equipment from ANSIR Facilities is available to all researchers from any institution in Australia and New Zealand on the basis of merit, as judged by the ANSIR Access Committee from a short proposal. Researchers have to meet the project operating costs and a modest mobilisation fee. Training is provided in the use of the portable equipment. The research can be outside Australia and New Zealand, and international partnerships are encouraged. Additionally, research programmes with industry are also possible.

Over the last few years, ANSIR and AuScope have also focussed on making legacy data available, with requirements that all new data collected through ANSIR are made publically available. Access to passive seismic date is now available through https://auspass.edu.au/ and for magnetotelluric data through https://nci-training.readthedocs.io/en/latest/_MT/MT_data_examples.html. The map of seismic stations across Australia shows the scope of these databases (Figure 1).

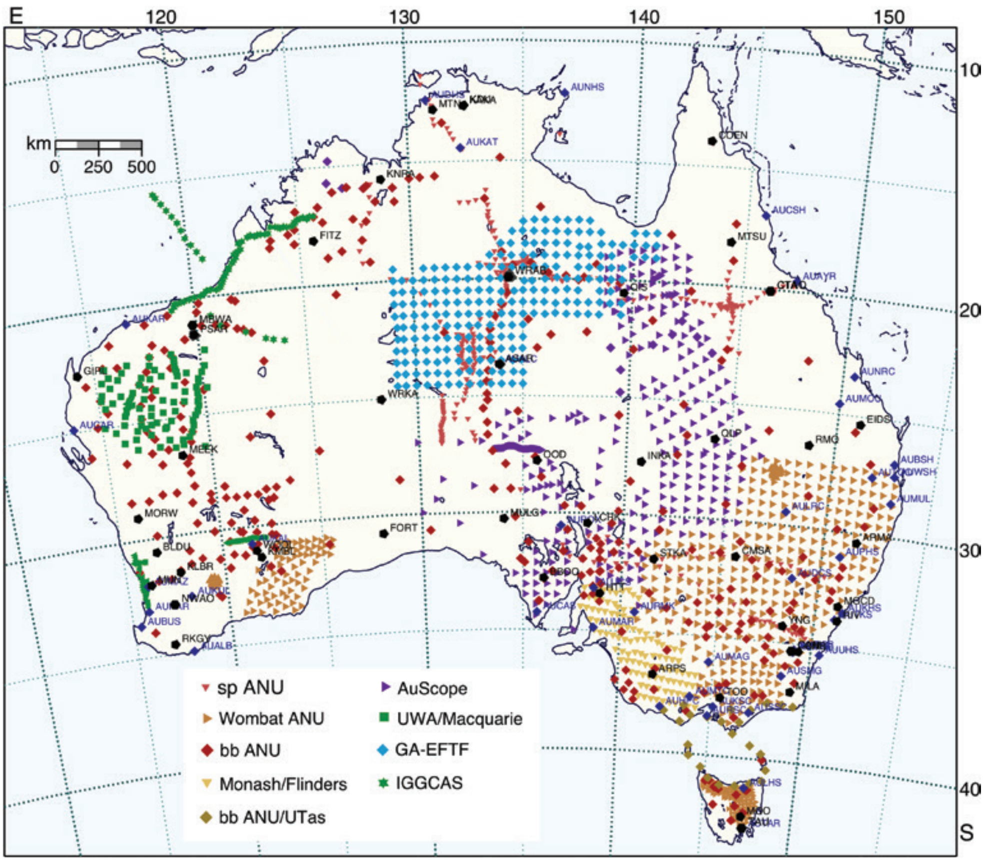


Figure 1. *Passive seismic stations across Australia.*

Our new web site location is under the AuScope Earth Imaging portal (https://www.auscope.org.au/ansir) which contains contact information and details of the application process. Applicants for access to ANSIR equipment and services should first contact the appropriate Scientific Coordinators to first discuss their needs for prospective projects, and then prepare a formal proposal which is submitted to the Chair of the ANSIR Access Committee, Dr Ron Hackney.

Magnetotelluric equipment

MT equipment being deployed in South Australia.

ANSIR has portable electromagnetic equipment including 25 Earth data logger long-period MT sets; 20 LEMI-424 long-period MT sets; up to 25 LEMI-423 broadband MT sets; and 5 Phoenix MTU-5C ultra-broadband MT sets. ANSIR also has five licences of Geotools (CGG), 5 licences of EMPower (Phoenix) and (TBA) access to CGG 3D MT Inversion software. These are based at the University of Adelaide. Please contact Prof Graham Heinson (graham.heinson@adelaide.edu.au) for more information and access.

Reflection seismic equipment

Vibroseis trucks on the Southeast Lachlan Deep Crustal Seismic Reflection Survey.

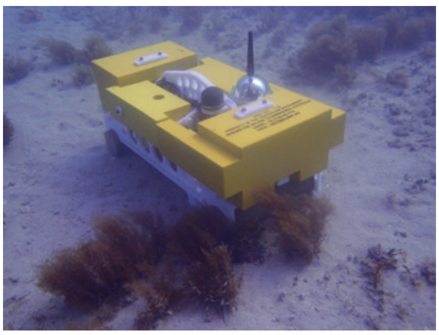
ANSIR is able to arrange reflection experiments for a wide variety of project goals, survey parameters, logistics, permitting and licencing requirements and consequent equipment requirements. Please contact Marina Costelloe (Marina.Costelloe@ga.gov.au) or Laura Gow (Laura.Gow@ga.gov.au) at Geoscience Australia for more information and access.

Passive seismic equipment

Passive seismic equipment deployed in New South Wales.

ANSIR has broad-band equipment including 50 sets of portable broad-band seismometers and high-fidelity, solar-powered recorders and 100 LPR-200 solid-state recorders with internal batteries that are suitable for deployments up to 3–4 months without servicing. Also, Lennartz LE-3Dlite 3-component 1 Hz seismometers (1 Hz); 50 Trillium Compact broadband sensors (3-component, up to 120s; and 50 new TerraSAWR recorders with internal batteries and compact solar panels. These are based at Australian National University. Please contact Dr Michelle Salmon (michelle.salmon@anu.edu.au) for more information and access.

Ocean bottom seismometers



Ocean bottom seismometers during deployment on the Australian NW margin, offshore Broome.

ANSIR equipment includes 17 sets of Guralp broadband ocean bottom seismometers (OBS). Users must be able to support trained technical personnel, and have scientific personnel with prior OBS experience on hand. Ship-time and insurance of the equipment while in transit and on seafloor is the responsibility of the proponents of experiments. These are based at Research School of Earth Science, Australian National University. Please contact Dr Alexey Goncharov (Alexey.Goncharov@anu.edu.au) for more information and access.

Petrophysical and sub-surface observatory equipment

University of Melbourne chief technician, Abe Jones, setting up a seismometer site in the Darling River region.

ANSIR can facilitate access to portable petrophysical and sub-surface observatory equipment including downhole seismic equipment and earthquake aftershock recorders.

These are hosted at AuScope's Subsurface Observatory at The University of Melbourne. Please contact Dr David Belton (d.belton@unimelb.edu.au) for more information and access.

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Geoscience Australia: News

Geoscience Australia (GA), in collaboration with the Geological Surveys of Western Australia, South Australia, Northern Territory, Queensland, New South Wales, Victoria and Tasmania has had an exceptionally busy couple of years for geophysical survey acquisition and processing (Figure 1).

Some specific highlights include:

AusAEM2

The Australian airborne EM surveying program (AusAEM) over northern Australia was suspended in October of this year at 72% complete whilst the aircraft undertakes work for the USGS. AusAEM commenced in 2018 and will eventually cover an entire area of 2.56 million km^2, from Hughenden in Queensland to Port Hedland in Western Australia (Figure 1). The remaining 138 700 line km will be completed by the middle of 2020 and is an integral part of the Exploring for the Future (EFTF) campaign, conducted in collaboration with the respective State and Territory geological survey agencies. Deliverables will include a full suite of inversions and integrated data products for groundwater resource analysis, and pre-competitive information for the identification of new mineral resources throughout Northern Australia. Inversion data for Queensland and NT parts of the program can already be accessed via the EFTF portal.

Tanami airborne magnetics and radiometric dataset

GA has recently completed additional processing of the Northern Territory 2018 Tanami airborne magnetics and radiometrics survey to generate a seamless merge for the 43 000 km^2 flown over The Granites and Mount Solitaire 250 k map sheets. Flown at 200 m flight line spacing and 60 m ground clearance, this new regional geophysical dataset acquired in collaboration with the Northern Territory Geological Survey (NTGS) provides significant resolution improvement over historical work. Since being released earlier this year, the dataset has already sparked considerable interest from mineral resource companies wishing to invest in this remote, relatively under-explored but highly prospective terrain.

The located and gridded data is now available via GA's e-catalogue system (https://ecat.ga.gov.au/ number 131406) or via the NTGS website.

Magnetotelluric data releases

Magnetotellurics (MT) is a passive geophysical method that uses natural time variations of the Earth's magnetic and electric fields to measure the electrical resistivity of the sub-surface. GA, in collaboration with the state and territory geological surveys and

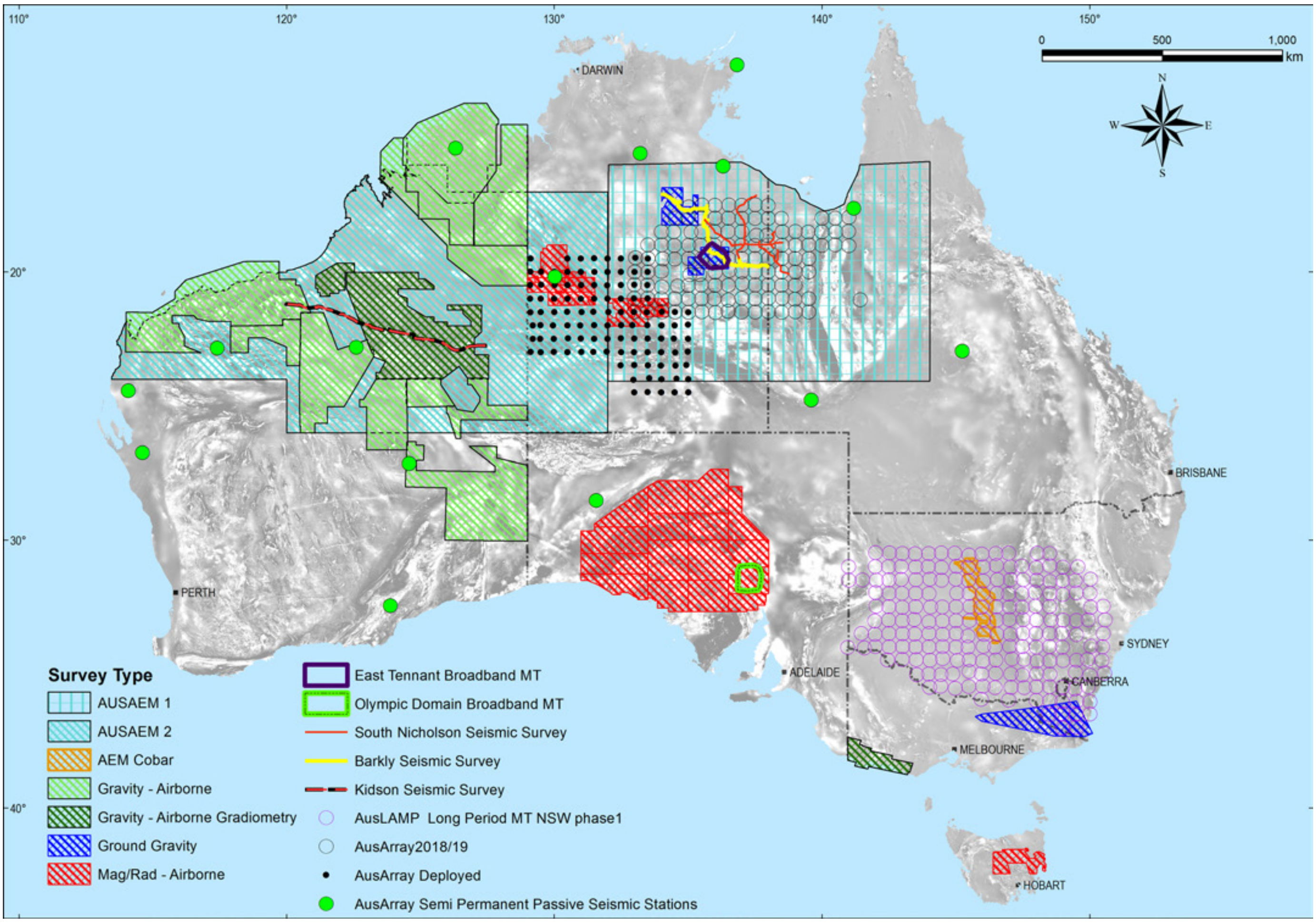

Figure 1. *2018–2020 geophysical surveys – completed, in progress or planned by GA in collaboration with State and Territory agencies.*

academia, undertakes both regional-scale and national-scale (i.e. the Australian Lithospheric Architecture Magnetotelluric Project – AusLAMP) magnetotelluric surveys. Data collected from these surveys is used to image the electrical conductivity/ resistivity structure of Australian continent lithosphere in three dimensions, and to identify and characterise major geological structures in the crust and upper mantle. Survey results provide new insight and valuable information for the Australian continent lithosphere framework, and address fundamental questions such as how the current geological structure was established, the nature of the geological processes, and how large-scale crustal and lithospheric structures control mineral deposition and hydrocarbon basin formation.

The MT survey results can be integrated with other national datasets, such as aeromagnetic, gravity, seismic tomography, geochemical, and geological datasets. The integration of these multidisciplinary datasets will help to develop a better scientific understanding of the lithospheric architecture and evolution of the Australian continent, highlight prospective areas for mineral and energy resources at a regional scale, and allow for assessment of geo-electric and other geological hazards.

The following MT datasets are expected to be released towards the end of this year and will be available via the GA eCAT website.

- Olympic Domain reprocessed data – The survey (see Figure 1) aimed to improve the understanding of the deformation zones and fluid pathways through the entire crust up to the sedimentary cover of the Olympic Domain. It was funded by the Geological Survey of South Australia's PaceCopper Initiative and was conducted by GA and the Geological Survey of South Australia.
- AusLAMP NSW raw and processed data, and resistivity model (see Figure 1). As part of AusLAMP, GA in collaboration with the Geological Survey of NSW are acquiring long period MT data across New South Wales on a half degree (~55 km) grid. Processed data collected up until August 2019 will be included in a release later this year. A resistivity model derived from these data, the AusLAMP Victoria data (Duan and Kyi 2018), and the eastern part of the Flinders Ranges survey (Robertson *et al*., 2016) will also be released. Interpretations from this new resistivity model will be released in a publication submitted to *Tectonophysics* (Kirkby *et al*., In Review).
- East Tennant raw and processed data. As part of the GA's Exploring For The Future Program, the East Tennant Magnetotelluric (MT) Survey (see Figure 1) was acquired to assist in regional stratigraphic drill targeting, and to map cover thickness and deep basin structural architecture. This data was collected in collaboration with the Northern Territory Geological Survey.

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Kirkby, Alison, Robert Musgrave, Karol Czarnota, Michael Doublier, Darren Kyi, Jingming Duan, and Ross Cayley. "Lithospheric Architecture of a Phanerozoic Orogen from Magnetotellurics: The Tasmanides, Southeast Australia." Manuscript submitted to *Tectonophysics*.

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Barkly deep crustal seismic survey

Australia is a vast continent which is largely under-explored in many regions. Large areas have poorly distributed data; some areas are completely untested for their resource potential. For industry to commit to exploration in frontier regions, additional pre-competitive information is needed to adequately evaluate the resource potential. This will effectively de-risk the area and give industry the confidence to initiate exploration activities. Our knowledge of prospective basins in northern Australia for natural resources is based on the currently available data. Historically, the most valuable data to predict oil and gas resources has been seismic reflection data to understand the architecture of the basins in conjunction with well data to analyse the potential of an active petroleum system.

As part of the Exploring for the Future (EFTF) Program, GA in collaboration with the Northern Territory Geological Survey (NTGS) acquired 812 km of deep crustal seismic reflection and gravity data from the southern McArthur Basin to the northern Mt Isa western succession (Figure 2). The survey commenced in September 2019 and data acquisition was completed in early of November 2019. Data from the Barkly Seismic Survey will be a great addition to the 2017 South Nicholson Seismic Survey data and links to the existing Beetaloo Sub-basin seismic data.

The Barkly Seismic data will assist in improving our understanding of basins and basement structures and also the energy, mineral and groundwater resource potential in Northern Australia. Following data processing, the new dataset will be publically released in 2020.

AusArray update

The Australian passive seismic array project (AusArray) is a collaborative, national survey between government and academia that acquires seismic waveform data. AusArray includes two components: (1) a movable array of 135 broadband seismic stations, arranged in a grid pattern, spaced ~55 km apart and deployed for 12 months, and (2) complementary semi-permanent higher sensitivity broadband seismic stations deployed for ~4 years. Key outcomes from AusArray are improved national three-dimensional velocity models of the Australian plate, and higher resolution three-dimensional seismic models in areas covered by the movable array from which physical properties of the lithosphere can be inferred from depths of a few metres to hundreds of kilometres.

Semi-permanent seismic stations provide a back-bone for movable deployments and compliment the Australian National Seismological Network (ANSN) operated by GA, ensuring continuity of seismic data for lithospheric imaging and quality control. Three new high-sensitivity broadband seismic stations were deployed in October 2019 (see Figure 3). These include DRYOZ and

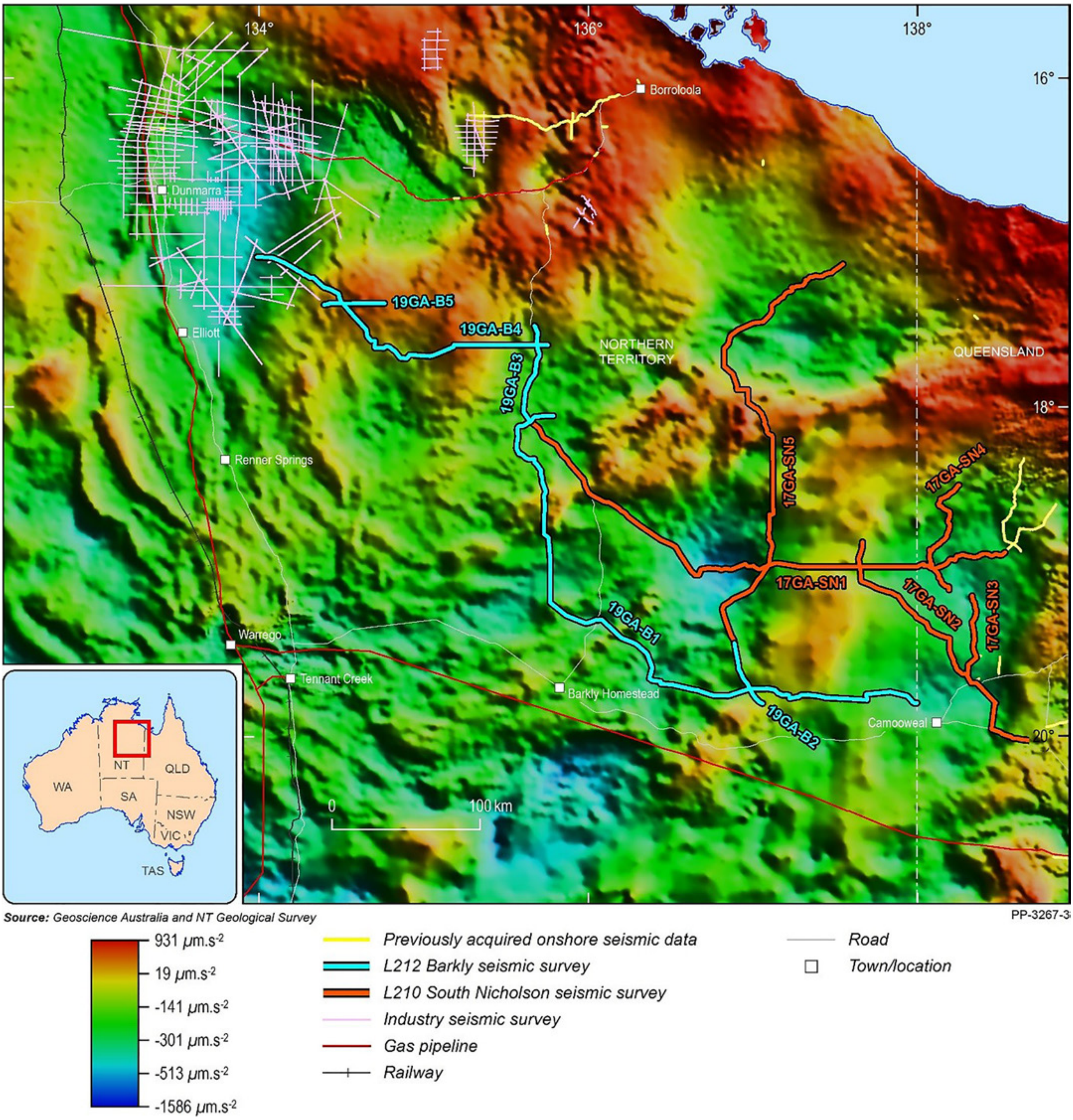

Figure 2. *Location map of the currently acquired Barkly seismic survey in the Northern Territory on a bouger gravity image.*

TEFOZ in Western Australia and BEUOZ in Queensland. Seismic instruments are deployed to depth of 3 m and will be in operation for a period of 4 years. At all three sites, Guralp CMG-3T high-sensitivity broadband seismic sensors are coupled with a Minimus digitizer which records seismic signal with sampling rate of 200 Hz. All permanent and semi-permanent seismic stations (including these three new stations) are registered with Incorporated Research Institutions for Seismology (IRIS) and data can be accessed through associated webpage.

As part of the Exploring for the Future (EFTF) program, data from the first 12-month deployment of the movable array (AusArray1; see Figure 3) is expected to be released in 2020, along with first generation of Australian lithospheric models. AusArray2 was serviced in November 2019 and will be retrieved in May–June 2020. As part of the service run, Multichannel Analysis of Surface Waves (MASW) data were also acquired and will be processed, modelled and publically released in the future.

Geoscience Australia's GADDS

Last but not least, GA's new geophysical data delivery system (GADDs) is set for

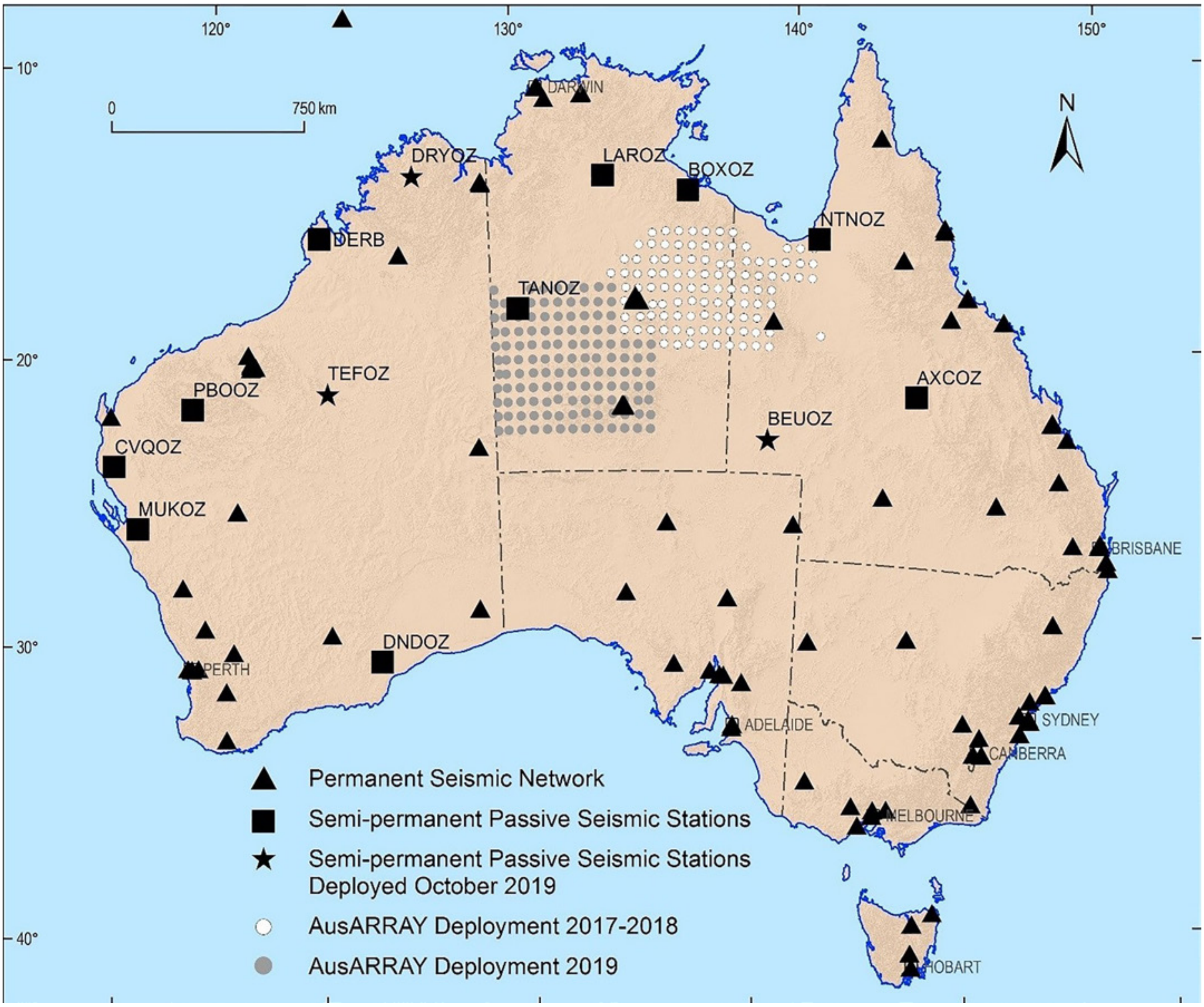

Figure 3. *Location of semi-permanent and permanent ANSN seismic stations across Australia as of October 2019, including the three newly installed semi-permanent stations. White and grey circles show location of AusArrray-1 and AusArray-2 movable array, respectively, deployed as part of the EFTF program. AusArray-1 was deployed from July 2017 to June 2018 and AusArray-2 was deployed in July 2019 and is expected to be retrieved in May–June 2020.*

initial release end of March 2020. Along with a more user-friendly GIS interface for grids (similar interface as per the EFTF portal: https://portal.ga.gov.au/), it will *eventually* have the capacity to clip, ship and zip located and point data from GA's electronic catalogue.

For the moment, GADDS will continue to faithfully deliver located datasets for surveys archived before June of this year. For located survey data acquired afterwards, please contact GA's client services clientservices@ga.gov.au or Mike Barlow on mike.barlow@ga.gov.au.

Update on geophysical survey progress from Geoscience Australia and the Geological Surveys of Western Australia, South Australia, Northern Territory, Queensland, New South Wales, Victoria and Tasmania (information current on 12 November 2019).

Further information about these surveys is available from Mike Barlow Mike.Barlow@ga.gov.au; (02) 6249 9275 or Laura Gow Laura.Gow@ga.gov.au 02) 6249 9605.

Table 1. Airborne magnetic and radiometric surveys

Survey name	Client	Project management	Contractor	Start flying	Line km	Line spacing Terrain clearance Line direction	Area (km²)	End flying	Final data to GA	Locality diagram (*Preview*)	GADDS release
Tasmanian Tiers	MRT	GA	TBA	Mar 2020	Up to an estimated 66 000	200 m 60 m N–S or E–W	11 000	May 2020	TBA	TBA	The National Collaborative Framework Agreement between GA and MRT is being updated.
Gawler Craton	GSSA	GA	Various	2017	1 670 000	200 m, various orientations depending on structure	294 000	26 Jun 2019	Aug 2019	http://www.energymining.sa.gov.au/minerals/geoscience/pace_copper/gawler_craton_airborne_survey	Anticipate QC and processing completion by Nov 2019. Will be released shortly afterwards.
Tanami	NTGS	GA	Thomson Aviation	14 Jul 2018	275 216	100/200 m 60 m N–S/E–W	48 267	2 Dec 2018	Jun 2019	195: Aug 2018 p. 16	Released
Mt Peake	NTGS	GA	MAGSPEC	10 Jul 2019	136 576	200 m N-S	24 748	TBA	TBA	Aug 2019	Acquisition complete

TBA, to be advised.

Table 2. Ground and airborne gravity surveys

Survey name	Client	Project management	Contractor	Start survey	Line km/ no. of stations	Line spacing/ station spacing	Area (km²)	End survey	Final data to GA	Locality diagram (*Preview*)	GADDS release
Kidson Sub-basin	GSWA	GA	CGG Aviation	14 Jul 2017	72 933	2500 m	155 000	3 May 2018	15 Oct 2018	The survey area covers the Anketell, Joanna Spring, Dummer, Paterson Range, Sahara, Percival, Helena, Rudall, Tabletop, Ural, Wilson, Runton, Morris and Ryan 1:250 k standard map sheet areas	Expected release before the end of Jun 2020
Little Sandy Desert W and E Blocks	GSWA	GA	Sander Geophysics	W Block: 27 Apr 2018 E Block: 18 Jul 2018	52 090	2500 m	129 400	W Block: 3 Jun 2018 E Block: 2 Sep 2018	Received by Jul 2019	195: Aug 2018 p. 17	Expected release before the end of Jun 2020
Kimberley Basin	GSWA	GA	Sander Geophysics	4 Jun 2018	61 960	2500 m	153 400	15 Jul 2018	Received by Jul 2019	195: Aug 2018 p. 17	Expected release before the end of Jun 2020
Warburton-Great Victoria Desert	GSWA	GA	Sander Geophysics	Warb: 14 Jul 2018 GVD: 27 Jul 2018	62 500	2500 m	153 300	Warb: 31 Jul 2018 GVD: 3 Oct 2018	Received by Jul 2019	195: Aug 2018 p. 17	Expected release before the end of Jun 2020

(*Continued*)

Table 2. Ground and airborne gravity surveys (*Continued*)

Survey name	Client	Project management	Contractor	Start survey	Line km/ no. of stations	Line spacing/ station spacing	Area (km²)	End survey	Final data to GA	Locality diagram (*Preview*)	GADDS release
Pilbara	GSWA	GA	Sander Geophysics	23 Apr 2019	69 019	2500 m	170 041	18 Jun 2019	Final data received Aug 2019	The survey area is in the Pilbara region in the northwest of Western Australia. Data acquired will be compiled into an update of the gravity anomaly map of Western Australia and help characterise regional geological elements in the area.	Expected release before the end of Jun 2020
SE Lachlan	GSNSW/ GSV	GA	Atlas Geophysics	May 2019	303.5 km with 762 stations	3 regional traverses	Traverses	Jun 2019	Jul 2019	TBA	Set for incorporation into the national database by end Oct 2019
TISA	NTGS	GA	Atlas Geophysics	2 Jul 2019	7821	2 km × 2 km grid	31 285	Sep 2019	Received by Jul 2019	TBA	Expected release before the end of Jun 2020

TBA, to be advised

Table 3. Airborne electromagnetic 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
East Kimberley	GA	GA	SkyTEM Australia	26 May 2017	13 723	Variable	N/A	24 Aug 2017	Nov 2017	TBA	TBA
Surat-Galilee Basins QLD	GA	GA	SkyTEM Australia	2 Jul 2017	4627	Variable	Traverses	23 Jul 2017	Nov 2017	188: Jun 2017 p. 21	TBA
Stuart Corridor, NT	GA	GA	SkyTEM Australia	6 Jul 2017	9832	Variable	Traverses	12 Aug 2017	Nov 2017	188: Jun 2017 p. 22	TBA
AusAEM2, NT-WA	GA	GA	CGG Tempest	May 2019	59 098 with areas of industry infill	20 km	1 074 500	TBA	TBA	201: Aug 2019 p. 16	72% complete. Acquisition suspended until aircraft returns in Jan 2020
Cobar	GSNSW	GA	NRG Xcite	13 Sep 2019	6701 with areas of industry infill	2.5 and 5 km	19 145	19 Oct 2019	Jan 2020	201: Aug 2019 p. 17	TBA

TBA, to be advised

Table 4. Magnetotelluric (MT) surveys

Location	State	Survey name	Total number of MT stations deployed	Spacing	Technique	Comments
Northern Australia	Qld/NT	Exploring for the Future – AusLAMP	166 stations deployed in 2018 - 19	50 km	Long period MT	The survey covers areas of NT and Qld. *Ongoing*
AusLAMP NSW	NSW	AusLAMP NSW	210 stations deployed to date out of 320	50 km	Long period MT	Covering the state of NSW. *Ongoing*
Southeast Lachlan	Vic/ NSW	SE Lachlan	Deployment planned to commence in Feb 2020	~4 km	AMT and BBMT	~160 sites in the Southeast Lachlan
AusLAMP TAS	TAS	King Island MT	4 stations deployed in Jun 2019. Survey completed.	<20 km	Long period MT	Covering King Island
East Tennant	NT	East Tennant MT	131 stations deployed in Aug 2019. Survey completed.	1.5 - 10 km	AMT and BBMT	132 sites planned covering an area northeast of Tennant Creek. Part of the MinEx CRC National Drilling Program
Cloncurry	QLD	Cloncurry Extension	Survey commenced in Sep 2019.	2 km	AMT and BBMT	Approximately 500 sites planned in the eastern concealed margin of the Mount Isa Province. This survey is an extension of the 2016 Cloncurry MT survey.

TBA, to be advised

Table 5. Seismic reflection surveys

Location	State	Survey name	Line km	Geophone interval	VP/SP interval	Record length	Technique	Comments
South East Lachlan	Vic/NSW	SE Lachlan	629	10 m	40 m	20 s	2D - Deep crustal seismic reflection	This survey covers the Southeast Lachlan Orogen crossing the Victorian-NSW border. Data acquisition was completed in Apr 2018. Raw data and processed seismic data has been released and are available via Geoscience Australia.
Kidson	WA	Kidson Sub-basin	872	20 m	40 m	20 s	2D - Deep crustal seismic reflection	Within the Kidson Sub-basin of the Canning Basin extending across the Paterson Orogen and onto the eastern margin of the Pilbara Craton. The survey completed acquisition on 8 Aug 2018. Data released in May 2019.
Barkly/ Camooweal	NT	Barkly sub-basin	810	10 m	30 m	20 s	2D - Deep crustal seismic reflection	Acquisition of 2D land reflection seismic data to image basin and basement structure in the Barkly region of the Northern Territory. Data acquisition commenced in Sep 2019 and is due to be completed 5 Nov 2019.

Table 6. Passive seismic surveys

Location	Client	State	Survey name	Total number of stations deployed	Spacing	Technique	Comments
Northern Australia	GA	Qld/NT	AusArray Phase 2	About 135 broad-band seismic stations	50 km	Broad-band 1 year observations	The survey covers the area between Tanami - Tennant Creek –Uluru and West Australian Border. The first public release of transportable array data is expected by end 2019. See location map in in *Preview* 201: Aug 2019 p. 16

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GEOLOGICAL SURVEY

OPEN DAY 2020

Friday 21 February 2020

8.30 am – 4.30 pm

Followed by a Sundowner

Esplanade Hotel, Fremantle

Cnr Marine Terrace and Essex Street

This is a great opportunity to hear presentations on the latest results from GSWA's geoscience programs, including collaborative work with CSIRO, Geoscience Australia, Curtin University, and the Centre for Exploration Targeting (CET).

Activities and results of the Exploration Incentive Scheme will be outlined including the launch of Round 21 of the Government Co-funded Exploration Drilling program.

Throughout the day there will be geological presentations, an extensive poster display, and demonstrations of online systems and technology innovations.

Register online at

www.dmp.wa.gov.au/GSWAOpenDay

For further information, call **(08) 9222 3646**

Government of **Western Australia**
Department of **Mines, Industry Regulation and Safety**

Geological Survey of Victoria: North Central Victorian Goldfields ground release

Victoria has re-emerged as an international minerals exploration destination, particularly for gold. A recent increase in minerals exploration activity, especially within the Victorian Goldfields region, has shown promising signs of the potential for new gold discoveries around former operations and under cover. Recent high-grade gold discovery and production success at the world-class Fosterville operation (near Bendigo) highlights the potential for high-grade gold discoveries and development opportunities in Victoria.

To explore this potential, the Victorian Government has released new areas for minerals exploration within the north central Victorian Goldfields region (Figure 1), via an international, open, competitive, merit-based tender.

The tender opened on 29 October 2019 and closes at 6pm (AEDT) on 31 January 2020. The tender documents are available at tenders.vic.gov.au.

A geological overview of the ground release area and the four blocks offered is provided in the tender documents, together with a list of reports and datasets that may be of assistance.

Geoscience information, datasets and tools from Geological Survey of Victoria (GSV) are publicly available including:

1. GeoVic – a spatial mapping tool that searches geospatial databases to display results as maps or tables;
2. Drill Core Library –GSV's facility at Werribee that houses drill core and cuttings from across Victoria;
3. Earth Resources Publications –The online collection of GSV maps, reports and digital data;
4. Geological Survey of Victoria Catalogue – Online access to all Earth Resources reports and data including those associated with open-file mineral exploration.

Geophysical exploration datasets available in the North Central Goldfields region include:

- Detailed airborne magnetics/ radiometrics
- Airborne gravity gradiometry
- Airborne time domain electromagnetics
- Detailed ground gravity
- Reflection seismic
- CSAMT and IP surveys

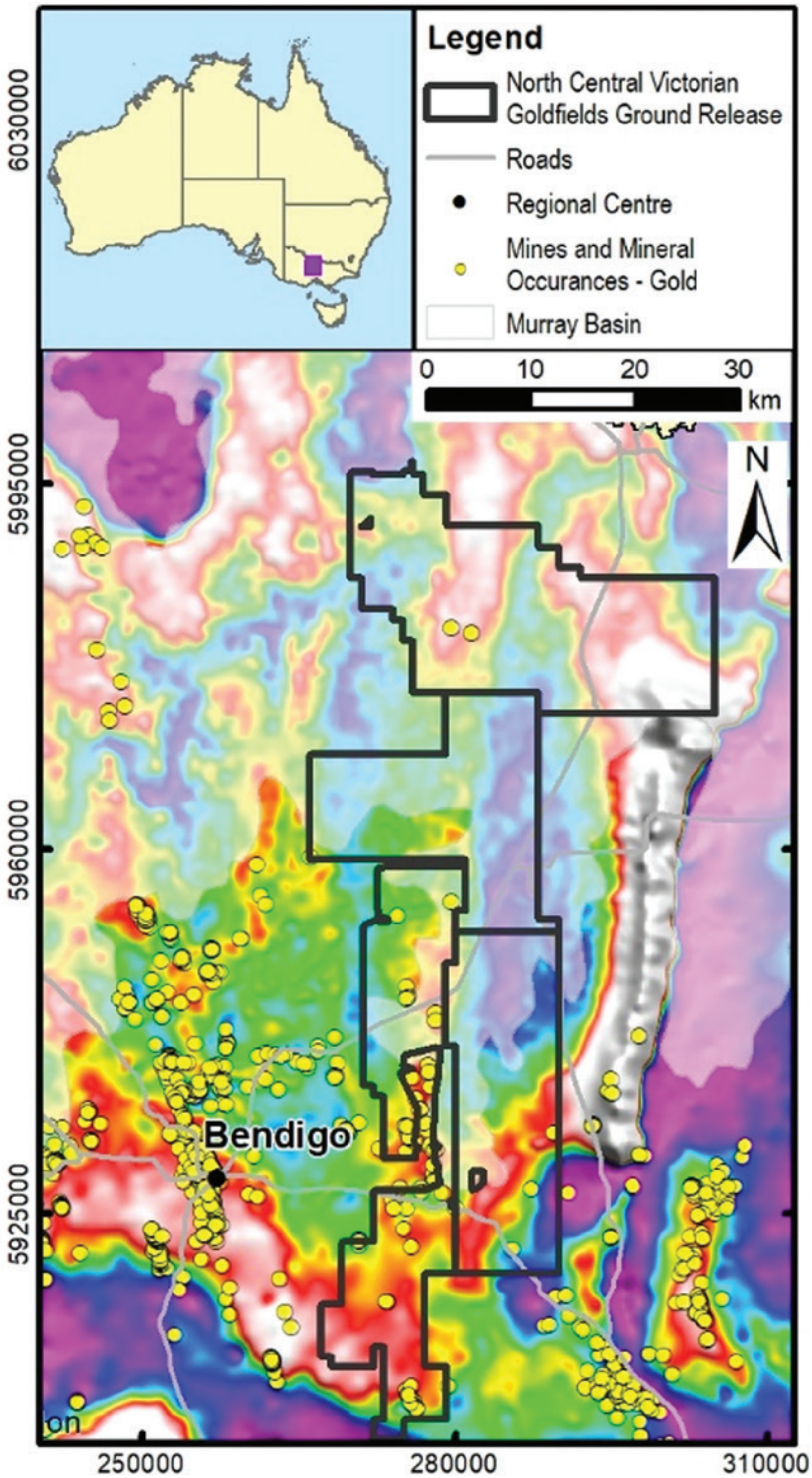

Figure 1. *North Central Victorian Goldfields Ground Release Blocks overlaid on terrain corrected Bouguer gravity with 25 km high-pass filter applied (white=high, magenta=low). Grey screen indicates areas under Murray Basin cover. GDA94MGA55 coordinates shown. Gold mines and occurrences are shown as yellow dots*

For more information about the tender, industry briefings, reports, data and geology visit https://earthresources.vic.gov.au/projects/north-central-victorian-goldfields-ground-release and https://earthresources.vic.gov.au/geology-exploration/maps-reports-data

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Geological Survey of South Australia: An update

Data now available from GCAS Regions 1A and 1B

The Gawler Craton Airborne Survey (GCAS) team are pleased to announce that the data and images for survey region 1A (Tallaringa North) and 1B (Tallaringa South), completed by Thomson Aviation Airborne Geophysical Survey, are now available for download. These highly anticipated data releases cover the north-western Gawler Craton, a true greenfields exploration frontier.

Data packages can be downloaded directly from the Gawler Craton Airborne Survey Community Information page and via SARIG (Figure 1).

The vertical magnetic gradient images of GCAS regions 1A and 1B, highlighting complex geological structure and detail, is shown in Figure 2.

We anticipate that data from the remaining blocks of the Gawler Craton Airborne Survey (Blocks 5, 6 and 9b) will released before the end of 2019. Further information can be found at energymining.sa.gov.au/minerals/gcas

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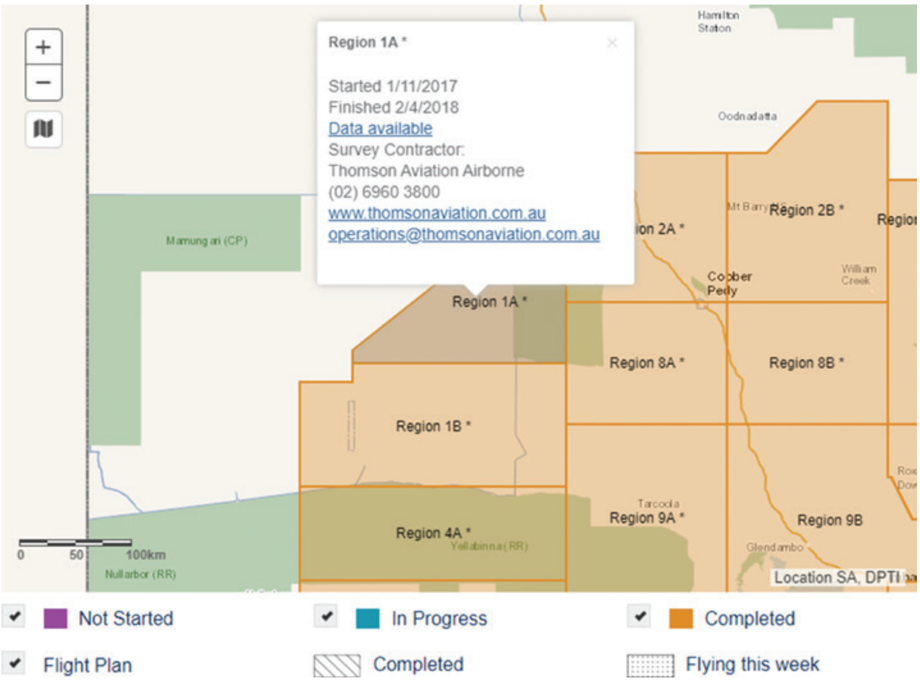

Figure 1. *GCAS data availability. Clicking on a survey region displays a link when data is available. Clicking the link opens a new window with survey information and data downloads.*

Marine MT deployment

Stephan Thiel and Kate Robertson headed to Port Lincoln last weekend, for an international geophysics collaboration with world leaders in marine magnetotellurics (MT), Scripps Institute of Oceanography, along with partners Geoscience Australia and the University of Adelaide. All hands were on deck for the deployment of 12 marine MT instruments in the Spencer Gulf, the first of its kind in South Australia in over 20 years (Figure 3). Funding for this project comes from the Geological Survey of South Australia, Geoscience Australia and AuScope. This pilot project expands the coverage of land MT sites to the continental shelf–geology does not stop at the coast line!

This survey will fill a significant gap in MT data coverage across the important eastern margin of the prospective Gawler Craton with a view to possibly extending the national AusLAMP project onto the

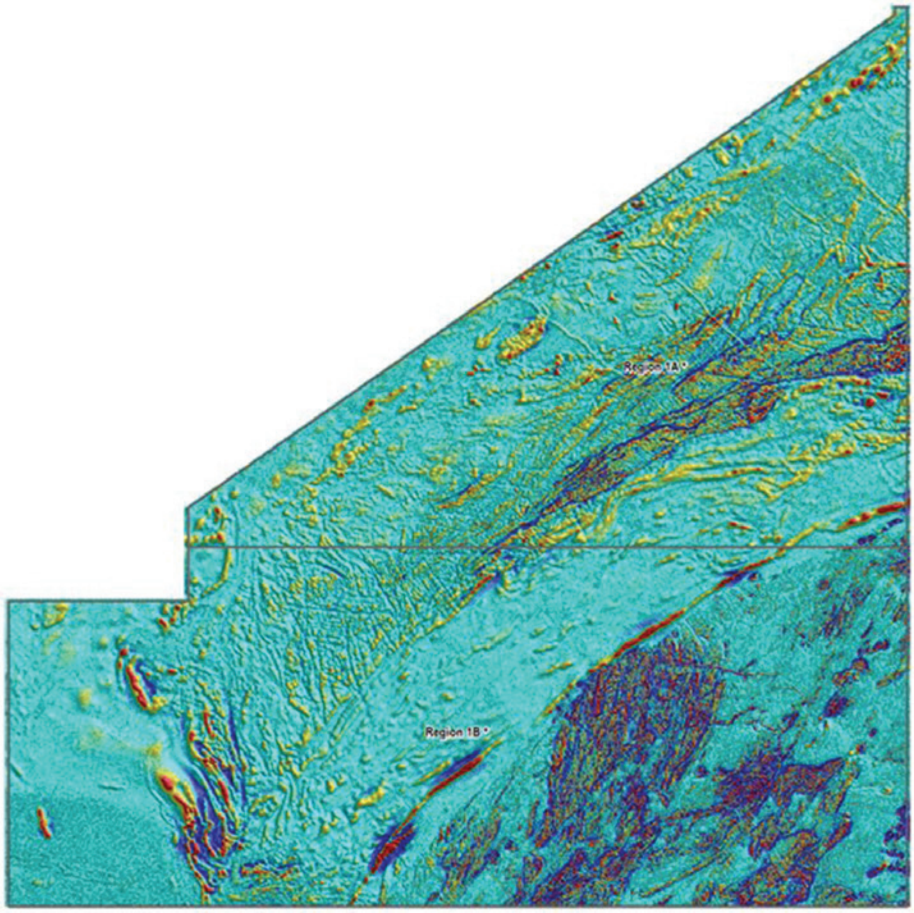

Figure 2. *Magnetic intensity image 1VD of reduced to pole TMI, imaging from north-west to south-east: The Nawa Domain, Mabel Creek Ridge, Tallaringa Trough, Karari Shear Zone and Christie Domain.*

Figure 3. *Kate Robertson (GSSA), Jake Perez (Scripps Institute of Oceanography, San Diego, US), Goran Boren (University of Adelaide), Stephan Thiel (GSSA), and Darren Kyi (Geoscience Australia).*

Figure 4. *The "Salt River" with the marine MT instruments on deck leaving for Spencer Gulf.*

continental shelf. The sites were deployed from a fishing vessel by Port Lincoln local Blaslov Fishing in a transect from Tumby Bay to the Yorke Peninsula (Figure 4). The instruments recorded magnetic and electric fields for 5 days at the bottom of the ocean before being retrieved. Data processing is underway.

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SEISMIX 2020– Abstract submission deadline extended

The abstract submission deadline for SEISMIX 2020 has been extended until Monday 9 December 2019. Please visit the Symposium Webpage to register and submit an abstract.

SEISMIX 2020 has been expanded to include the latest technological and scientific developments in the application of seismic methods. The range of conference topics include:

As there is room on the page, please dot point these topics e.g.

- Innovative seismic acquisition and processing techniques
- Active and passive seismic interferometry
- Active continental margins and subduction zones
- Mid-ocean ridges and oceanic lithosphere, global processes – collisions and accretion
- Comprehensive geological interpretation
- Near surface seismology – case histories
- New developments and advances in DAS applications
- Novel seismic imaging and inversion methods
- Moho in 3D
- Special topic - ET resource potential and unusual case histories, lessons learnt.

Symposium Registration is inclusive of an evening icebreaker, daily lunch and dinner, tea and coffee breaks, a gala dinner and Rottnest Island day trip. Please note accommodation is **not included** in the conference package.

A post-conference field trip is planned to take place after the symposium – from Friday 20 March to Friday 27 March. The trip will cover an extensive territory of the south-west of Western Australia, taking place over eight days and stretching over 2000 km. The aim of the field trip is to show WA's geological wonders and the immense beauty of the Southern Ocean coastal plains. One of the key topics during the field trip revolves around the




potential role of seismic methods for exploring and characterising these unique geological settings.

Further details relating to the Symposium and Post-conference field trip can be found on the webpage http://seismix2020.org.au/.

Important dates

Monday 9 December 2019: Abstract submission closes

Friday 20 December: Abstract acceptance notification date

Friday 3 January 2020: Registration closes

15 – 19 March 2020: Symposium

Friday 20 – Friday 27 March 2020: Post-conference field trip

Canberra observed

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Australian business R & D investment a national disgrace

BERD continues to decline as percentage of GDP

According to the Australian Bureau of Statistics (ABS), the business resources devoted to research and experimental development (BERD) during 2017–18 amounted to $17 438 M (https://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/8104.02017-18?OpenDocument). This was an increase of 4.6% over the 2015–16 numbers, but in terms of a percentage of GDP it represents a decline of 0.1% to be less than 1%. The chart in Figure 1 shows how BERD, as a percentage of GDP, has fared over the last 25 years. It is not a pretty sight.

Table 1 shows the actual numbers, not corrected for inflation.

The four industries with the greatest contribution to BERD are the professional, scientific and technical services ($5113 M or 29%), manufacturing ($4599 M or 26%), financial and insurance services ($2847 M or 16%) and mining ($1050 M or 6%). These four industries accounted for 78% of total BERD (see Figure 2).

Professional, scientific and technical services recorded the largest increase (up $1362 M or 36%) followed by manufacturing (up $691 M or 18%). Conversely, mining and financial and insurance services recorded the largest decrease, down $826 M (44%) and $368 M (11%) respectively.

Comparisons with OECD countries are difficult because most produce these statistics annually, but at present Australia only produces them every two years, because of funding cuts to the ABS.

The most recent OECD data I could find just contains the total R & D efforts. These include investments from both governments and industry (https://data.oecd.org/rd/gross-domestic-spending-on-r-d.htm) for 2017. The OECD average investment is about 2.4% of GDP and as the best estimate for Australia is 1.8% of GDP and going down.

Location of expenditure

New South Wales and Victoria continued to have the highest levels of BERD, with $6820 M (39% of total BERD) and $4550 M (26% of total BERD) respectively. Western Australia showed the largest decrease down $490 M (24%), followed by Queensland down $43 M (2%).

BERD incurred overseas recorded the largest increase in dollar terms, up $534 M (66%). Perhaps, this is why the mining sector has declined so much – a lot of research is undertaken overseas.

Impacts of efficiency dividends

The BERD situation will get worse because of the declining budgets and the death by a thousand cuts to national science institutions. CSIRO, Geoscience Australia and the ABS will all have to shed staff because of the efficiency dividend. These and other agencies not only undertake their own research but

Table 1. Business resources devoted to R&D.

	2008/09	2009/10	2010/11	2011/12	2013/14	2015/16	2017/18
Current prices $M	17 291	16 760	18 007	18 321	18 849	16 659	17 438
Human resources PYE	53 886	57 936	56 511	64 906	78 839	70 467	74 991

PYE = Person Years of Effort

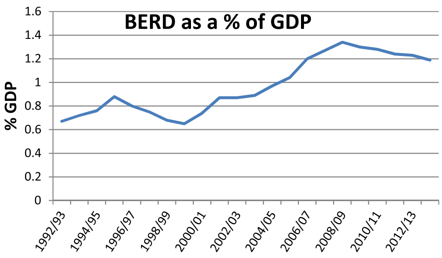

Figure 1. *Business expenditure devoted to research and experimental development (BERD) in Australia from 1992–2018. After 2011 the ABS only produced annual numbers for alternate years. The data for the missing years have been estimated by interpolation.*

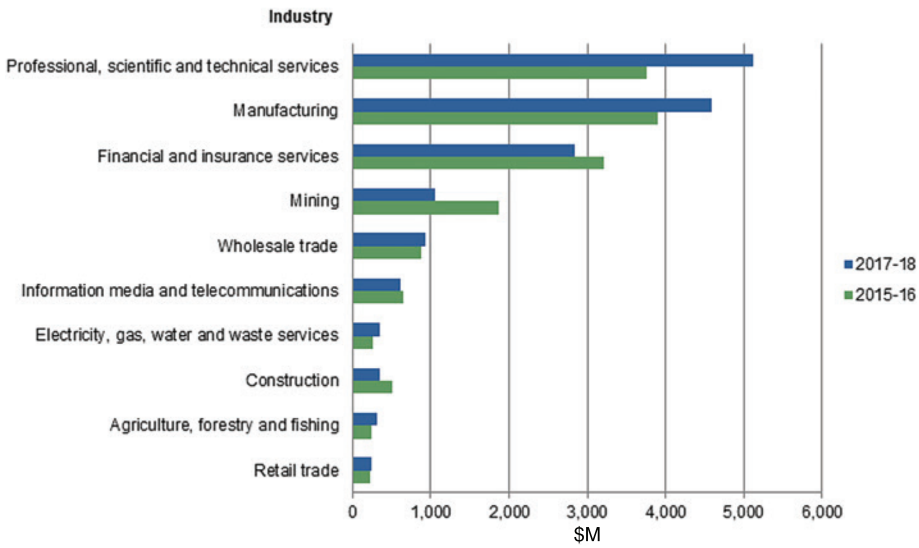

Figure 2. *Australian BERD, by top ten industries. Notice that in percentage terms the mining sector declined the most. Source: ABS https://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/8104.02017-18?OpenDocument*

co-operate with industry on a wide range of research projects – or at least they used to.

One would have thought that, in the 21st century, the need for a strong research base and a corresponding set of national statistics on a whole range of parameters would be a no-brainer – but not now in Australia. The funding freeze is hitting hard, and the government does not seem to be interested building high-tech education and research facilities. We seem to be muddling along from election to election, with the politics controlling most of the government's decisions. It's a national disgrace.

The drought package

The government's response to the current drought is a typical example. It looks like a knee-jerk reaction, which will provide interest free loans, special grants in drought affected areas to provide support for isolated children in non-government schools, build more roads and fund the operation of Adelaide's de-salination plant so that river water can be allocated to grow silage.

There was no mention of a water management plan for the future, but we can all relax because Major General Stephen Day is now Coordinator-General for Drought.

I am not sure why building roads is going to help managing our water resources, and although the upgrade to the Wyangala Dam near Cowra and a new Dungowan Dam to be built near Tamworth will increase the water storage, it would be good to see some calculations based on expected temperature and rainfall that show the benefits of these investments. If there has been any modelling, it has been well hidden. At both these locations the annual evaporation rate is approximately 2 m per year. Will it be best to store the water in dams or encourage a re-charge of the underground water resources? We don't know.

Then, there is the elephant in the room. How should the land and water be used? Is it sensible to grow cotton and rice anymore? How do we reduce the demand for water in the Murray Darling Basin so that it can be sustainably managed? Governments have been wrestling with these issues for many years, but the *status quo* is not working.

Eventually the Commonwealth Government is going to have to take water management by the scruff of the neck and 'bring it on'. We need common sense and evidence-based policies to manage our water. In the meantime, it's all very frustrating.

Gold Council reports strong demand for gold

The World Gold Council reported a strong demand for gold in its October 2019 monthly report (file:///C:/Users/David/Downloads/2019-October-fund-flows.pdf).

In October, global gold-backed ETFs[1] and similar products saw US$1.9 B of net inflows, primarily across Europe and North America, increasing their collective gold holdings by 44.4 t to a new record high of 2900 t. Global gold-backed assets under management have grown 38% so far in 2019, partially driven by the gold price appreciation; this figure is 10% below its 2012 high, when the price of gold was above US$1700/oz.

The global evidence is reflected in the Australian gold information, as shown in Figure 1. This figure shows the gold price in $A/oz, adjusted to 2019 dollars, from the Reserve Bank's tables (https://www.rba.gov.au/statistics/tables/); the quarterly exploration investment in the search for gold x 5 and adjusted to $A in 2019 (https://www.abs.gov.au/Ausstats/abs@.nsf/glossary/8412.0); and the Australian quarterly gold production from mines, from the Department of Industry's website (https://publications.industry.gov.au/publications/resourcesandenergyquarterlyjune2019/index.html).

The plots speak for themselves but, it is evident that the gold production is close to record levels. The price of gold, although somewhat volatile, has been steadily increasing over the last 10 years and exploration expenditure is bounding ahead. All-in-all a very optimistic picture for the gold explorers.

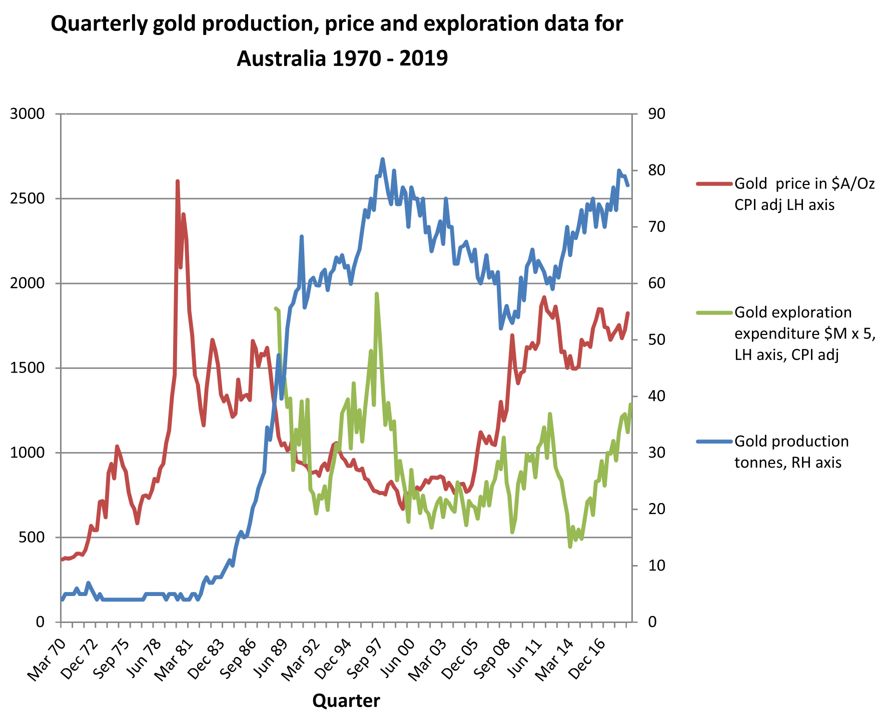

Figure 1. *Australian quarterly gold production 1970–2019, exploration investment from 1989–2019 and the gold price in $A. See the text for more information.*

[1] Gold backed Exchange Traded Funds (ETFs) are securities designed accurately to track the price of gold.

Education matters

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Field day for Queensland students

Geophysics students have a hunger for making the connection between class-room theory and field instrumentation and measurement. The Queensland Branch of the ASEG has particularly strong links between universities (UQ and QUT) and industry, and this year the tradition continues with a field day at Gap Geophysics Pty Ltd, looking at instrumentation for EM surveys, especially unexploded ordnance (UXO) detection. Nick Josephs brings us the story.

On October 4, Gap Geophysics hosted a half-day tour of their facilities at West End for students from two Brisbane-based universities. The success of the last few years geophysics student field trips prompted this industry-student collaboration. This was organised by representatives from the QUT Natural Resource Society (Alan Pearse), the UQ Geosociety (Harrison Button), the QLD branch of ASEG (Nick Josephs) and the Operations Manager at Gap (Dan Eremenco). Students studying geophysics and geology, including honours and PhD candidates came along to find out more about geophysical applications and mineral exploration.

Students arrived in the offices at West End, introduced themselves and were given a quick safety induction and orientation. Stephen Griffin, (Technical Services Manager, Gap), led an introductory presentation and described Gap, its history of innovation, its subsidiaries and their specialities. It was great to see the amount of innovation and application of technology to solve real-world exploration problems. Will Rowlands (Operations Manager, Gap Explosive Ordnance Detection EOD) presented some of their international work and case studies which blew the audience away. Students were mostly impressed that there was so much travel to both developing and developed countries on the EOD team. After Will and Stephen answered the students' questions, we stopped for a coffee and came back to see some of their newest tech and R&D including 360° video of using UAV's for geophysical surveying.

Stephen then showed off a display of current and historical equipment that Gap has iteratively improved, how far innovation has come. and explained how the technology has evolved. Major changes include the shift from heavy-plastics to light weight carbon-fibre, from metal backpack supports to plastic orthopaedic moulded supports for the ground acquisition crews, the step-change increments in the number of cycle recordings, and the massive payoff achieved as a result of miniaturisation of GPS navigation technology.

Doug Williams (Project Technician, Gap EOD) went through their non-ferrous UltraTEM system for detecting unexploded ordnance (UXO) and described how through working with mechanical engineers, GAP was able to design custom deployment systems for their technologies. Finally, we saw internals for a new airborne integrated EM and a magnetic sensor designed to sling beneath a drone; this really rounded off how quickly the industry is moving by utilising new technology.

The 2019 field trip was insightful and allowed the students to better understand the application of geophysics and how it can solve real exploration problems and improve public safety, via its ordnance detection team. It's crucial for our industry to keep in touch and educate students on the tools that will solve the problems they will face once out in industry. This

Stephen Griffin (GAP) describes innovations in EM instrumentation over time, especially achievements in miniaturisation. Watching on: Alan Pearse (QUT), Dale Harpley (UQ), Bodee Bignell (UQ), Calum Kowalski (UQ) and Dan Eremenco (GAP).

Doug Williams (GAP) outlines the UltraTEM trailer-mounted system for detecting non-ferrous UXO. Learning the story from left: Dale Harpley (UQ), Bodee Bignell (UQ), Calum Kowalski (UQ), Anthony Caracella (QUT), Alan Pearse (QUT) and Nick Josephs (Energeo).

will undoubtedly set these students apart from those without such knowledge, and help them further their careers.

I would particularly like to thank Alan Pearse (QUT), Callum Kowalski (UQ), Dale Harpley (UQ), Anthony Caracella (QUT) and Bodee Bignell (UQ) for taking time and helping on the day.

It's always good to see keen and up-and-coming students ready to tackle industry challenges. A big thanks is due to the Gap Geophysics team for taking valuable time out of their day to educate our students.

Lastly, if you are in the greater Brisbane Area and have geophysical presentations or instruments or even cool new tech examples to show off to small groups of eager geoscientists, feel free to contact me.

Nick Josephs
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Inaugural Dr Peter Milligan Student Award for Geophysics

Rebecca McGirr

Rebecca McGirr, of the Earth Dynamics Group at Research School of Earth Sciences, Australian National University, has been awarded the inaugural Dr Peter Milligan Student Award for Geophysics. The award, given by the ACT Branch of the Australian Society of Exploration Geophysicists, commemorates the contributions to geophysics of Dr Peter Milligan (1951–2019), and especially his contributions to the magnetic, gravity and radiometric maps of the Australian continent. At the presentation of the award in November, Rebecca gave the "Dr Peter Milligan Student Lecture", being a presentation of her research on Antarctic mass loss and glacial isostatic adjustment measured by space gravity missions.

Abstract of the inaugural "Dr Peter Milligan Student Lecture"

Over a period of 15 years, the twin GRACE satellites mapped the Earth's mean and time-variable gravity field with unprecedented accuracy. The success of the GRACE mission has been instrumental in advancing scientific understanding of both natural and anthropogenically induced variations in the hydrological cycle, ice-sheet mass balance, ocean dynamics and sea-level change. The success of the GRACE mission has since lead to the launch of its successor, the GRACE Follow-On (GRACE-FO) mission in a bid to continue the GRACE time series of time-variable gravity fields. Despite the undeniable success of both missions, many obstacles have prevented the estimation of highly accurate temporal gravity fields. For example, noise contained in the observations limit the resolution of the solutions, while difficulties in separating surface and sub-surface mass change signals convolute estimates of ice-sheet mass loss, particularly in Antarctica.

In this lecture, estimates of mass balance in Antarctica from GRACE observations of the temporal gravity field are discussed. This includes approaches that have taken to reduce the impact of instrumental noise on estimates of the temporal gravity field using digital filtering techniques, and a discussion of problems with current methods of estimating the contribution of post-glacial adjustment to Antarctica's mass balance.

Theses in geophysics submitted to Australian universities in 2019

Australian National University, Australian Capital Territory – PhD theses

Veronika Emetc, Australian National University: *Combining physics-based and statistics-based approaches to model calving in Antarctica.*

Surface and basal crevasses are deep fractures in ice that are observed on the surface and the base of the Antarctic ice sheet/ice shelves, respectively. They are a direct precursor of formation of rifts in ice shelves and a consequent calving or breaking off of icebergs. Modelling of calving is crucial for better estimation of the ice mass balance in Antarctica because ice shelves act like a supporting mechanism for the inland ice preventing it from accelerating into the ocean. While there have been a number of studies that attempted to parameterise calving, each of them has limitations that do not allow to apply them to all the Antarctic ice shelves on a large scale. A more comprehensive calving model needs to include not only parameterisation of calving at ice fronts, but also the history of fracturing of the ice that led to a calving event such as formation, advection and propagation of both surface and basal crevasses. Towards improving a calving parameterisation in ice sheet models we constructed a set of sub-models for predicting surface and basal fracturing, vertical and horizontal propagation as well as advection. Combining statistics-based and physics-based approaches we developed a preliminary calving model that includes the full history of rifts and crevasses, from their initiation to the final break off at the ice front.

Siyuan Tian, Australian National University: *Forecasting drought impacts with the assimilation of satellite water content retrievals.*

Drought poses the greatest threat to freshwater availability and food security, affecting larger areas for longer periods than any other natural hazards. In many regions, droughts increase in frequency and severity due to climate change. As a slow developing natural disaster, better estimates of water availability can be valuable for forecasting droughts and their impacts on ecosystem, agriculture and food security. With accurate knowledge of root-zone soil water and groundwater dynamics, effective planning of water resources and agriculture can be made months in advance. However, the simulated root-zone soil moisture and groundwater are often highly uncertain due to the unpredictable nature of soil water and groundwater dynamics caused by human activities such as water extraction and irrigation. Ground-based and remotely sensed measurements of water content are often limited in both spatial coverage and temporal resolution. Therefore, quantifying the change of water availability and its impacts on vegetation conditions at large scales remains largely unexplored.

For the first time, contrasting satellite observations of water presence over different vertical domains have been assimilated into a global water balance model, provided unprecedented accuracy of soil moisture pro le and groundwater storage estimates. The water availability at different depths observed from soil moisture (SMOS) and space gravity (GRACE) missions provides an opportunity to separate total water storage vertically into different layers through data assimilation. However, combining these two data sets is challenging due to the disparity in temporal and spatial resolution at both vertical and horizontal scales. SMOS provides global high spatial and temporal resolution (i.e. 40 km ^{2}, 3-day) near-surface (0–5 cm) soil moisture estimates from microwave brightness temperature observations. In contrast, the GRACE mission provides accurate measurements of the entire vertically integrated terrestrial water storage column, but it is characterised by low spatial and temporal resolutions (i.e. 300 km ^{2}, monthly). An ensemble Kalman smoother based global data assimilation system was developed to resolve the discrepancy between model and observations in space and time.

The use of data assimilation integrates these two measurements to effectively constrain model simulations and to accurately characterise the vertical distribution of water storage. Compared with model estimates without the assimilation or single-variant assimilation, joint assimilation typically led to more accurate soil moisture profile and groundwater estimates with improved consistency with *in situ* measurements. The improved water storage estimates integrated at different depths were used to determine the vegetation accessible storage in association with vegetation growth and surface greenness. Accessible storage reflects a combination of vertical root distribution and soil properties, and its spatial distribution correlates with aridity and vegetation type. Skilful forecasts of vegetation conditions are achievable several months in advance for most of the world's drylands, which offers exciting new prospects for the improvement of drought early warning systems to help reduce human suffering and economical and environmental damage.

Umma Jamilla Zannat, Australian National University: *Network effect in geocenter motion.*

Geocenter motion is the motion of the centre of mass of the Earth system with respect to the geometric centre of figure of the solid Earth surface because of the continual deformation of the Earth by geo-physical processes. This motion is important both in theory and in practice to understand and interpret various mass transport phenomena and their consequences, such as sea-level rise, post-seismic relaxation, polar ice melting, and glacial isostatic adjustment. The International Terrestrial Reference Frame (ITRF) is realised using measurements of the relative motion between satellites orbiting around the centre of mass on one hand and stations placed on the Earth surface on the other. Therefore, reliable modelling of the geocenter motion is vital for the stability and the accuracy of the ITRF. In turn, the interpretation of many geo-dynamic quantities of current interest, such as the mean sea-level, depends heavily on the quality of the adopted reference frame. Space geodetic measurement of the true geocenter motion, however, is difficult due to the discrete and therefore incomplete sampling of the Earth surface by geodetic stations. In other words, there is a discrepancy between the centre of figure of the Earth surface and the centre of network of the stations, called the network effect, arising from the sampling bias of the geodetic network.

In this work, we develop a method to estimate the magnitude of the network effect for a network of a given size N. For a given crustal deformation model, we consider the Helmert parameters of transformation between the centre of figure frames before and after the deformation event. Our proposed estimate for the network effect, which we call the "expected bias", is the standard deviations of the changes in these parameters by the event as measured by a random network of the size N. We show that, in accordance with probability theory, the expected bias scales as 1/ p N, and we provide an explicit formula for this estimate in terms of the vector spherical harmonics expansion of the displacement field. We assess the effectiveness of the expected bias as an estimate of the network effect by simulating the displacement fields for two illustrative geo-dynamical processes: (instantaneous) co-seismic deformation due to great earthquakes, and (time-dependent) elastic deformation due to surface water movements. We accordingly concentrate on the

instantaneous changes and the secular drifts in the Helmert parameters for the two cases respectively. We found that in both case studies the network effect is often as large as the changes in the Helmert parameters themselves. Hence, current space geodetic networks are indeed inadequate for verifying the geocenter motion predictions by geophysical models accurately. Nevertheless, our simulations validate the expected bias to be a reasonable estimate of the network effect. Finally, we propose an alternative definition of the centre of network frame that assigns a weight proportional to the Voronoi cell surrounding a station to its measurements. We show that it can significantly reduce the network effect and improve the detection of geocenter motion in most cases.

Curtin University, Western Australia – Honours theses

Thomas Boyle, Curtin University: *Stochastic forward modelling of AVO responses, Dampier Sub-basin, Western Australia.*

Utilising hydrocarbons as an energy source is still predicted to increase by approximately 30% for natural gas and approximately 20% for oil by 2040 owing to a slow transition into renewable energy. The exploration for hydrocarbons is consequently still necessary. Simultaneous to this, the difficulty, risk and cost of exploration is increasing as more complex reservoirs are explored for. This makes the tool of Quantitative Interpretation (QI) paramount.

The specific QI workflow implemented in this study, is the forward modelling of amplitude versus offset (AVO) responses using elastic property models from a Dampier Sub-basin rock physics study undertaken by DownUnder GeoSolutions as the inputs. The modelled AVO responses were then compared to the genuine AVO response observed at hydrocarbon discoveries identified in the region, with the hope of identifying seal and reservoir lithologies, and also fluid fill properties. This has been completed to test the prospectivity of exploration permit WA-X in a region of the North Carnarvon Basin with a historically low drilling success rate (8%) caused by poor definition and prediction of one or more of: trap, seal or reservoir elements. A lack of direct hydrocarbon indicators and the inability to accurately predict objective sand intervals contribute to the poor pre-drill definition and prediction.

Four depth structure maps were generated across the study area: Top Upper Angel Formation, Top Lower Angel Formation, Top Eliassen Formation and Top Legendre Formation. At the conclusion of this, two prospects were identified. Prospect A is a tilted fault block associated with an antithetic fault to the main Rosemary Fault System and has a Middle Jurassic Legendre Formation reservoir. Prospect B is a stratigraphic basin floor fan trap with an Oxfordian Eliassen Formation reservoir.

The QI workflow predicts that the seal and reservoir lithologies at Prospect A are a silty claystone and a sandstone with intermittent claystone (50/50) respectively. It was not possible to predict the fluid properties as the sandstones within the target interval have a high pore stiffness, resulting in small seismic fluid sensitivity. Deterministic volumetric analysis for Prospect A provided an in-place oil volume of 10.5 million barrels. The QI workflow was not undertaken for the Prospect B prospect. This was because a feasibility study implemented for the similarly configured Hurricane Field concluded that a QI workflow was not suited for a reservoir with these rock physics properties. The most likely reason for this is the high variability in the elastic property models across the study area for the Late Jurassic Eliassen Formation sandstone. At the conclusion of the study the lack of any prospects with estimated resource volumes of sufficient size to be of economic interest suggests that exploration permit WA-X is not very prospective for further exploration.

Nicholas Berdal, Curtin University: *Characterisation of lithium pegmatite using geophysical methods in the Pilbara Craton, Western Australia.*

The increase in the demand for raw battery materials has evolved the mining sector to focus upon the exploration and extraction of lithium. Historically, geological field mapping and well data have been the primary methods of lithium pegmatite exploration. These methods are intrusive, high cost and inefficient for detailed subsurface mapping.

Little literature exists regarding the direct use of geophysical techniques for the exploration of lithium pegmatite, resulting in such methods to be approached with hesitancy. The use of geophysics for the characterisation of pegmatite is highly dependent on the peripheral geology of the deposit, where distinguishable resistivity and magnetic susceptibility contrasts are of great importance.

The implementation of electrical resistivity imaging and time domain EM were to investigate the geological context of a pegmatite deposit, which was to assist in determining the lithological content surrounding the pegmatite. Surface mapping techniques were also utilised to provide relationships between surface topography and the geological conditions, which were to distinguish subsurface continuity in correlation with the ERI and TEM datasets.

The applied geophysical methods provided significant information regarding the topographic and subsurface geological content surrounding the known pegmatite deposit, allowing the deposit to be distinguished in the highly heterogeneous environment. These findings promote the implementation of geophysical methods for the exploration of lithium pegmatite, and reveal the benefits of a cross-interpretation between surface and subsurface geophysics, and drill data.

Lauren Found, Curtin University: *Assessment, characterisation and removal of noise in drone-based aeromagnetic survey data.*

As modern airborne magnetic surveying advances, so too does the need to understand and characterise noise as it plays a fundamental role in the assessment of survey quality. In the field of drone platforms, new sensors and systems are being developed as the weight and expense of existing sensors present an issue to the more lightweight drone system, and this could provide new challenges in addressing survey quality and noise.

The primary goal of this project is to understand the input each of the noise sources contributes to the recorded signal of a drone-based magnetic survey, and provide a simple workflow for minimising their impacts without affecting the rest of the signal that can easily be reproduced to allow data quality comparisons between different drone-based datasets as well as between old and new surveying systems.

A drone-based survey in Victoria, Australia was flown and found to have numerous sources of noise.

These included cultural influences, a mechanical setup issue that was enhanced by prevailing weather conditions and an effect introduced during processing. Three workflows were used to investigate the effect and magnitude of this noise, two focusing on filtering gridded data, and one focusing on filtering line data prior to gridding. The workflows were then successfully applied to a second drone-based survey over a different geological target to observe their effectiveness in removing noise whilst leaving signal intact.

Timothy Hill, Curtin University: *Comparative analysis of seismic inversion techniques for hard rock environments.*

The Nova-Bollinger ore deposit is one of the most significant discoveries of recent years. Initially discovered in 2012, the orebody contains 13.1 Mt of ore (2.03% Ni, 0.83% Cu, 0.07% Co) constituting a multi-billion-dollar resource, owned and operated by Independence Group NL (IGO). Extensive effort in the form of drilling and geophysical surveying has been undertaken in recent years in order to further characterise the existing orebodies and to determine structural controls on orebody deposition.

In 2017, a 2D seismic survey was undertaken by HiSeis Pty. Ltd. on behalf of IGO, which revealed two super-domains separated by the Nova Fault, as well as several fault systems and intrusive bodies. Based on the results of the 2D survey, a 58 square-kilometre 3D seismic survey was commissioned in 2018, revealing possible relationships between structural and stratigraphic controls and the ore deposits, as well as identifying several prospective targets, prompting further drilling.

The primary objectives of this study were to form a robust link between the seismic data and available borehole data, produce and compare seismic inversion techniques for efficacy and to determine whether seismic inversion techniques could help discriminate prospective lithology in the form of mafic intrusives from non-prospective lithology. The overall purpose for this research was to determine the applicability and methodology of Quantitative Interpretation (QI) techniques in hard-rock environments. Current methods are qualitative in nature, and if seismic inversion is successful a more robust approach to stratigraphic drill targeting could potentially lead to significant cost and time savings in the hunt for the next Nova-Bollinger.

Five inversion methods were used and compared for a 2D seismic section. The methods used were: Coloured Inversion, Model-Included Coloured Inversion, Band-limited Inversion, Soft-Constraints Model-Based Inversion and Hard-Constraints Model-Based Inversion. In the coloured inversion section, structures could be identified as breaks in lithology. In the model-based techniques, it became clear that the starting model was of paramount importance as this model dominated the final inversion. The lowest error between borehole log and the inverted log was achieved with the Hard-Constraints Model-Based Inversion method (1054.88 (m/s)*(g/cc)) however the best balance between model input and seismic data was qualitatively achieved using the Band-limited inversion method. In most cases, the known Nova and Bollinger orebodies were not able to be located, however discrimination between intrusive zones and meta-sediments was found to be possible.

James Regan, Curtin University: *Locating lithium-bearing pegmatites using the seismic reflection method in Tabba Tabba, Pilbara, Western Australia.*

The demand for lithium has increased in the previous years due to its many uses and extensive applications. In Western Australia the element is found in the mineralised form and is commonly held within pegmatites. Most of the production of lithium within WA comes from the Greenbushes Province in the south west, but can also be found in sufficient quantities in the Pilbara, where the region presents major shear zone structures. Exploration for pegmatites can be problematic as the structural formations are characteristically complex and vary in orientation and thickness. This means that straight forward interpretation of drill holes can be misguiding.

The question then lies with, whether or not we are able to get a better understanding of how these deposits trend within the subsurface? A possible solution to this may be achieved by applying geophysical methods. In the past, geophysical exploration over these deposits has struggled even though contrasts in the physical properties of pegmatites and the surrounding host are present. However, imaging the structures remains difficult. The regions in which they are formed are commonly quite complex geological settings, resulting in additional complications in the accuracy of the geophysical data.

The results achieved by the 2D seismic method do not provide reliable mapping of the deposits on its own. However, the combination of different geophysical methods increases the confidence in targeting of pegmatite formations and the overall understanding of the geology.

Jake Tomlinson, Curtin University: *A practical comparison of transient electromagnetic sensors over a conductive target in regional Western Australia.*

Time domain electromagnetic surveys are the primary geophysical method employed to locate economic base-metal deposits. Such exploration surveys utilise a transient electromagnetic sensor to record the secondary magnetic field produced by targets of interest. This thesis presents a comprehensive analysis of the high temperature SQUID and fluxgate magnetometer which are commonly used in time domain electromagnetic surveys. The fluxgate magnetometer has a long and extensive history in geophysical exploration, but with limited near surface deposits left undiscovered exploration companies have turned to a more advanced receiver antenna. Superconducting quantum interference magnetometers are regarded as the most capable readily available sensor.

The quality of data recorded by a transient electromagnetic sensor in a practical setting is dependent on internal and external factors. The dominant internal factors influencing the receiver's ability to accurately record the secondary electromagnetic field decay is sensitivity, intrinsic noise level and sensor limitations. These factors are unique to individual magnetometers and often specific to the magnetic effect used to measure the magnetic field variations. Dominant external factors include geological noise sources, geomagnetic variations and survey design.

Analysis of time domain electromagnetic data acquired from two separately conducted surveys permitted the assessment of the internal and external factors listed above.

Key outcomes of the research saw variations in receiver sensitivities and intrinsic noise levels dictating the abilities of the magnetometers to accurately identify known subsurface targets. In survey 1 the Phoenix coil failed to illuminate three confined conductors imaged by the B-field magnetometers. In survey 2 the fluxgate magnetometer misidentified two known parallel

subsurface targets as one homogenous body. The high temperature SQUID was able to accurately separate the two targets. Comparison of decay analysis between survey 1 and 2 saw an order of magnitude improvement in the amplitude of magnetic field variations recoverable by the fluxgate magnetometer. The same comparison saw two orders of magnitude improvement in the variations detectable by the high temperature SQUID. Survey 1 represented poor survey design whilst survey 2 represented optimal survey design. Results of the comparison highlight the influence external factors have on receiver's ability to accurately record the secondary electromagnetic field decay.

University of Adelaide, South Australia – PhD thesis

Dennis Conway, University of Adelaide: *Advances in Magnetotelluric Modelling: Time-Lapse Inversion, Bayesian Inversion and Machine Learning.*

This thesis presents advancements to the area of magnetotelluric (MT) modelling. There are three main aims to this work. The first aim is to implement an inversion to model time-lapse MT data in a temporal dimension. The algorithm considers the entire dataset at once, with penalisations for model roughness in both the spatial and temporal dimensions. The inversion is tested on synthetic data, as well as a case-study from a coal-seam gas dewatering survey. Second is to explore the problem of non-uniqueness in MT data inversion by implementing a 1D Bayesian inversion using an efficient sampler. The implemented model includes a novel way of regularising MT inversion by allowing the strength of smoothing to vary between different models. The Bayesian inversion is tested on synthetic and case-study datasets with results matching known data. The third aim is to implement a proxy function for the 3D MT forward function based on artificial neural networks. This allows for rapid evaluation of the forward function and the use of evolutionary algorithms to invert for resistivity structures. The evolutionary search algorithm is tested on synthetic data sets and a case-study data set from the Curnamona Province, South Australia. Together, these three novel algorithms and software implementations represent a contribution to the toolkit of MT modelling.

University of Adelaide, South Australia – MPhil thesis

Joe Rugari, University of Adelaide: *Electrokinetic methods and applications in Australian aquifer settings: High-dimension electrical tomography imaging and neural network filtration techniques.*

Being the driest continent in the world, there is a significant reliance on groundwater resources within many communities and industries throughout Australia. Particularly in regional areas with low rainfall and surface runoff resources, the underlying groundwater availability plays a pivotal role in population capacity and economic prosperity. Whilst the importance of groundwater resources is indisputable, many aspects of its real world homeostatic processes, in both macro and micro scales, remain difficult to decipher and explain.

Within Australia's fractured rock aquifer systems, attributed with storage of the largest volume of groundwater resources nationally, there is still only fragmented understandings of several of their principal components and capacities. This is inclusive even of key aquifer characteristics, such as total volume estimations, regeneration sources, and their flow or transportation methods. Improved modelling capabilities and techniques based on prominent and robust hydrogeological principals are continually emerging from advancing technologies, new data sources and forward thinking. However, within the field data retrieval facet of hydrological research a seemingly slower evolution is taking place. A vast quantity of aquifer information is still derived directly from intrusive observation wells. Although the plethora of information these wells can yield in modelling is invaluable, there are some profound limitations that must still be addressed.

Wells are costly to establish due to drilling expenses, can only provide single point information, and can also be disruptive to the homeostasis of the system. The self-potential method is an electro-kinetic geophysical method that has recently been re-identified as an immensely promising groundwater technique. It is a fast, passive, inexpensive surface technique which requires no drilling. Uniquely and most importantly however, it is the only geophysical method that is directly sensitive to not only the presence of groundwater, but also the physical flow of groundwater due to its generation of a measurable electrical signal. Previously regarded as a predominately qualitative geophysical tool, contributing factors including advancements in low-cost instrumentation and processing capabilities have meant self-potential surveys can now provide spatially significant quantitative data for a range of groundwater modelling inputs such as permeability.

The method has been recurrently reviewed since its early conception in international geophysical literature through to modern times. However, only a small quantity of this peer reviewed research has been conducted within Australia. A lesser extent of published literature therefore deals in particularly with addressing the challenges of both our harsh climate, and surface and geological conditions. With our own unique geological and hydrogeological settings, current and future challenges regarding securement of groundwater resources, and increasingly common practice of industrial geotechnical processes such as fracking, all research and findings are vital contributions to furthering our understanding of potential groundwater applications for self-potential methods on home soil. This research thesis provides analyses of multiple electro-kinetic field research projects. New self-potential datasets have been collected in the Adelaide Hills targeting stimulated fractured-rock aquifers up to 40 m below surface - a considerably deep target for the method, particularly within highly conductive Australian geological conditions. Previously collected geophysical datasets from the Adelaide Hills have been reprocessed from two to four-dimensions utilising newly constructed algorithms, then reanalysed with supporting geophysical datasets. And finally, a long term (46 day) self-potential monitoring programme was conducted at a commercial-use porous media aquifer to investigate novel techniques in both autonomous groundwater flow presence investigation, and environmental noise filtering methodologies for a given self-potential dataset.

This research endeavours to draw further conclusion on the self-potential methods prospective as a value-adding and commercial viability modern geophysical technique in

Australian groundwater research. Additionally, employing use of artificial neural networks (machine learning) for the self-potential autonomous detection and environmental noise filtration methods, we highlight the current gap in geophysical literature regarding the combination of these techniques. A light is drawn to the combined techniques immensely promising future of potential applications and contributions within the wider electrical geophysics data automation and filtration space. Much akin to our continual pursuit for mineralisation deposits, Australia is searching deeper than ever before for crucial groundwater supplies as shallower sedimentary aquifers are becoming fully utilised or depleted. As we move forward towards this new era of deepening natural resources, we must further develop both old and new tools which can enhance clarity of understanding within these challenging hydrogeological systems.

University of Adelaide, South Australia– Honours theses

Celina Sanso, University of Adelaide: *Compositional controls on the thermal conductivity of metamorphic rocks.*

Thermal conductivity is essential for determining heat flow within the Earth, which is necessary for geothermal investigations, accurately modelling tectonic and volcanic processes, and predicting petroleum maturation. Although currently, conductivity can be measured on hand samples, it can be impracticable to make regional and subsurface models due to time and expense required. In this study, an analysis on the compositional controls on thermal conductivity of metamorphic rocks is completed. Thermal conductivity was determined using an optical thermal scanner on 168 metamorphic samples with prior major oxide element analyses. Density is determined through models, as well as measured using Archimedes' principle. The results show that thermal conductivity varies between 1.698 to 5.226 W m^{-1} K^{-1}. When observing the relationships there is no trend between thermal conductivity and the major oxides. However, anisotropy has a log normal distribution with a mean of –2.098 and a standard deviation of 1.346, and produces a weak negative correlation with conductivity of –0.566. A correlation occurs between SiO_2 and K_2O, where a maximum anisotropy potential peaks between 60% to 65%, and approximately 5%, respectively. The modelled density is successful in determining the measured density, allowing the density for future samples to be determined indirectly. From the results of the study, more considerations need to be taken when observing the compositional controls in the future for metamorphic rocks. A narrower range of rock types or chemistry could be considered, along with the mineralogy of the samples. Singular provinces should also be considered to determine if conductivity for metamorphic rocks occur regionally. Furthermore, a focused study on how the P-T conditions of a singular rock type change with thermal conductivity can be assessed. Such analyses will improve estimates of subsurface conductivity and the ability to accurately estimate crustal temperatures.

Lachlan Loader, University of Adelaide: *The Eyre Peninsula conductivity anomaly, South Australia.*

A major electrically conducting structure has been spatially located in the southern Eyre Peninsula, South Australia. The structure extends from the continental margin inland along the eastern margin of the Eyre Peninsula, trending north-northeast for approximately 150 km. In order to provide a two-dimensional image of the crust orthogonal to the conductor's strike, 39 broadband (1000 to 0.01 Hz) magnetotelluric sites were collected with approximately 2 km separation across the peninsula. A smoothed 2-D inversion model demonstrated that the conductor appears centred beneath a topographic high, structurally bound at the east by the transpressional Kalinjala Shear Zone and resistive Donington Suite granitoids, and the Sleaford Complex to the west. The main features from modelling are: (i) east of the Kalinjala Shear Zone, a region of high resistivity (> 1000 ohm/m) relates to the Donington Suite granitoids; (ii) the late Archaean Sleaford Complex (2480–2420 Ma) bordering the Donington Suite granitoids features a lower, wider resistivity range between 5 to < 600 ohm/m, and is near-vertical in the top 12 km; (iii) the lowest resistivity structure of < 0.1 ohm/m occurs at a depth of 5–10 km, and appears to terminate at a depth of ~15 km. The low resistivity structure correlates with banded iron formations, and is credibly the result of biogenically deposited graphite in marine sediments, which migrated to become concentrated in fold hinges during the Kimban Orogeny; and (iv) the conductor is collocated with a ridge of high gravity (+ 200 to 500 mGals). The origin of this high gravity may be due to a mafic intrusive block of oceanic crust, compressed during the continental collision of the Kimban Orogeny. Utilising the constraints of the 2-D model, a regional 3-D forward model was developed which shows agreement with compiled legacy data sets.

University of Sydney, New South Wales – Honours theses

Cian Clinton-Gray, University of Sydney: *The interplay of tectonics, eustasy and surface processes on the North Slope of Alaska since the Jurassic.*

The North Slope of Alaska is a resource-rich region located within the circum-Arctic that has experienced a complex tectonic and geodynamic history. Although regional palaeogeographic reconstructions for the North Slope of Alaska have been interpreted from the geological record, a process-based understanding of the source-to-sink system accounting for both the landscape and sedimentary basin evolution of the region has not been undertaken.

Additionally, the interaction of the complex tectonic (including deep mantle flow) and climatic forces and their influence on the development of sedimentary basins is not well understood. This study presents the first quantitative forward modelling approach to explore sediment dynamics on the North Slope of Alaska by using the surface process numerical modelling code, pyBadlands. It aims to investigate the influence of tectonics (including deep mantle flow), eustasy and isostasy (including flexure) on the source to sink system on the North Slope to better understand its evolution since the Jurassic. This was achieved by incorporating time-dependent dynamic topography estimates from numerical models linking plate motions and mantle flow. A series of temporally and spatially evolving tectonic events that represent the tectonic topography that results from rifting and collisions were also constructed. Horizontal displacements were integrated into the models by incorporating plate velocities extracted from the tectonic reconstructions using GPlates.

The models capture the North Slope's counter-clockwise rotation away from the

Canadian Arctic Islands and consequent collision with the Koyukuk oceanic-island arc, which resulted in the uplift of the Brooks Range and the formation of the adjacent foreland basin. They also reproduce the sediment depositional trends and main provenance areas on the North Slope of Alaska as observed from the sedimentological record.

The spatial variation in dynamic topography through time resulted in tilting of the basin which influenced sediment routing directions. Sea-level fluctuations were found to significantly slow the depositional system, trapping more sediment in the proximal basin. Notably, during the main phase of deposition in the basin (115 to 100 Ma), eustasy resulted in the accumulation of up to 200–400 m thicker sequences. Cross-sections of the modelled deposition of the Aptian to Cenomonian clinothem across the foreland basin were extracted to more closely analyse the shelf margin evolution. They revealed that the models reproduce the large-scale stratal geometries observed from the seismic record, as well as the shelf margin trajectory shift at ~105 Ma where stratal stacking patterns shift from dominantly progradational to more aggradational. They suggest that sealevel acted to decrease the progradation rate by ~6 km/Myr during the early longitudinal filling of the basin (~115 to 105 Ma), and that a dynamic subsidence of at least ~50 me experienced by the basin between 110 and 100 Ma was a contributing factor to the abrupt trajectory shift.

This study demonstrates the importance of linking deep Earth processes to landscape evolution models to gain a better understanding of the long-term evolution of sedimentary basins.

Joe Ibrahim, University of Sydney: *Mechanical stratigraphy, structural style and the evolution of fold and thrust belts.*

Fold and thrust belts form as the crust accommodates shortening due to compressional tectonic forces. The structural architecture of fold and thrust belts varies widely and is influenced by a multitude of factors including the driving boundary conditions, the amount of shortening and the level of basement involvement (i.e. thin-skinned vs thick-skinned tectonics). Here, we investigate how the mechanical properties of rocks control the structural style of fold and thrust belts.

Mechanical stratigraphy refers to the mechanical layering present in a stratigraphic column, involving the succession of competent and less competent lithologies. For a given set of boundary conditions and amount of shortening, the mechanical stratigraphy is expected to influence the partitioning of shortening between folds and thrusts, their respective distribution pattern, their respective wavelengths, and possibly the nature and expression of their interaction. An understanding of the mechanical stratigraphy of a fold and thrust belt is crucial for assessing structural traps, fluid flow, and refining geologic interpretations.

In the first part of the thesis, we run two-dimensional, coupled thermal and mechanical, numerical experiments utilising the Underworld framework to explore the influence of mechanical stratigraphy on the structural evolution of fold and thrust belts. We calibrate our numerical parameters such that we are able to simulate the formation of natural fold and thrust belts. This enables us to systematically investigate the structural styles brought on by the mechanical layering of competent and incompetent units within a stratigraphy. We find that multiple wavelengths of deformation are activated in our models.

A landscape-scale wavelength of deformation that forms due to the mechanical contrasts within the overall stratigraphic package, and a more local wavelength of deformation that forms as a result of mechanical heterogonies within single units. This wavelength of deformation gives way to a more complex and heterogenous set of structures. Our work has led us to conclude that the position of competent layers within a multilayer, in combination with the ratio of competent to incompetent rock will have a significant influence on strain partitioning within thin-skinned fold and thrust belts.

In the second part of the thesis we calibrate a mechanical stratigraphy for the structural styles found in the Papuan Fold Belt, utilising previous knowledge about the strain partitioning of the region, and a set of well-imaged structures. We aim to propose a coherent assemblage of structures in the less constrained parts of the Gobe region, which is characterised by the convergence of two varying structural trends. Our models demonstrate the control mechanical stratigraphy has on multiwavelength deformation of the Papuan Fold Belt. We document the interaction and interference between the thick- skinned Darai Plateau trend, and the thin-skinned Papuan Fold Belt trend.

In our preferred model, the convergence of these structural trends is accommodated through the formation of a pop-up wedge in the hanging wall of two conjugate faults, which are part of a duplex-like structure which consists of a series of hinterland-dipping stacked horses. Our results show that the competent units, such as the Darai limestone deform via faulting, whereas the incompetent Mesozoic sediments tend to fold, and contain multiple detachment horizons. Models with a calibrated mechanical stratigraphy are able to reproduce structures similar to those found in the New Guinea Fold Belt, reveal the structure of the lesser constrained areas of the fold and thrust belt, and illuminate subsurface geometry in the region.

Monash University, Victoria – Honours theses

Hannah Williamson, Monash University: *How does the geophysical response of complex geology translate undercover? An example from the Wonomo Fault, southern Mount Isa Inlier.* **ASEG Research Foundation supported project**

The southern extension of the Mount Isa Inlier has been largely neglected for exploration because of logistical and technical difficulties of exploring undercover despite the likelihood of this region hosting large mineral systems. Geophysical data provides powerful information on the petrophysical properties of lithologies undercover which can be used to make interpretations of buried geology. However, the reduction in resolution of aeromagnetic and gravity data with depth and lack of surface constraints increases the level of ambiguity of interpretations. This study analyses the

limitations of geophysical methods by simulating a well constrained 2D profile at depth to understand how structures such as the Mount Isa Fault will translate undercover.

We focus on the Wonomo Fault, a likely segment of the Mount Isa Fault. This study recognised the Wonomo Fault to be the southern extension of the Mount Isa Fault due to similarities in (1) relationship dividing the Sybella Domain with the Leichhardt River Domain; (2) geometry as a steeply west dipping structure; and (3) protracted history of early normal movement and late reverse reactivation. The fault forms a ~1500 m wide high strain zone characterised by intense shearing, mylonite development and quartz blows. The geophysical response corresponds to a linear zone of magnetite destruction trending parallel to bedding. An angular unconformity between the Leichhardt Superbasin and the Calvert Superbasin was found parallel to the Wonomo Fault within 600 m to the east. The analysis of structures at depth found responses corresponding to narrow structures with little offset are typically lost when buried under 500 m of cover while structures juxtaposing units of contrasting petrophysical properties can be interpreted beyond 1000 m and further enhanced using vertical derivative data sets.

The ambiguity of interpretations was demonstrated where an angular unconformity produced a similar geophysical response to the Wonomo Fault. The importance of using field mapping to constrain geophysical interpretations and understand the expected lithologies and geometries was therefore demonstrated.

Gianni Mercuri, Monash University: *Architecture of the Coolgardie Domain: Implications for Yilgarn mineral systems.*

The Coolgardie Domain is located within the Kalgoorlie Terrane, of the Yilgarn Craton, Western Australia. The Domain has been relatively under studied in relation to the other Domains within the Kalgoorlie Terrane such as the Kambalda and Ora Banda Domains despite hosting numerous high-grade gold camps such as Tindal's and Greenfields. Field mapping, geophysical mapping, litho-geochemistry, drill core logging and thin section analysis were all utilised to better understand the architecture of the Coolgardie Domain and assess the Au related mineral system within the domain.

A geophysical interpretation constrained by field observations and measurements as well as drill hole data revealed a distinct E–W trending architecture that likely formed as a result of local geometries and rheological contrasts between the granitic intrusions and greenstone belts. Downhole magnetic susceptibility data showed an apparent relationship between Au grade and a high magnetic susceptibility response. This relationship was observed in both the Coolgardie and Depot Domains, which are separated by the sinistral Kunanalling Shear Zone. This downhole association is likely mapping out a redox boundary, possibly similar to the St Ives camp.

Litho-geochemistry of the basalts within both the Coolgardie Domain and the Depot Domain showed that the basalts between the two areas are distinctly different from each other and that previous Domain subdivisions of the Kalgoorlie Terrane that included the Depot Domain as part of the Coolgardie Domain are no longer valid. The combination of magnetic susceptibility measurements, detailed graphical logging and structural mapping as well as mapping redox relationships and mineralogy across the Coolgardie Domain may prove a vital exploration since it can assist in highlighting zones of Au mineralisation.

The Coolgardie Domain shares similarities with other felsic intrusion dominated domains such as the Southern Cross domain and recognising these relationships provides insight to the mineralisation mechanisms in the Coolgardie Domain.

University of Tasmania, Tasmania – Honours thesis

Joseph Behan, University of Tasmania: *Petrophysical and geophysical characterisation of high-grade mineralisation at Fosterville Gold Mine, Victoria.*

Joseph's project was kindly supported by Kirkland Lake Gold, owners of the Fosterville mine. The two main aims of the project were: to assess the potential geophysical response of the recently discovered bonanza-grade free-gold-in-vein Swan ore system, and to evaluate the application of high-resolution ground magnetic surveying for mapping stratigraphy and structures associated with refractory wall-rock-hosted gold mineralisation contained within disseminated sulphides.

Density, magnetic susceptibility, inductive conductivity, galvanic resistivity, induced polarisation and P-wave velocity measurements were collected on a suite of 270 samples from the Swan ore system, its enclosing alteration zone and host sequence. These data were used to create potential field, resistivity, induced polarisation and seismic reflection forward models of the likely ore-system responses and hence to recommend appropriate geophysical exploration strategies.

Approximately 50 line-km of ground magnetic data were acquired, processed and interpreted in an area adjacent to a former open pit where a large surface diamond drill programme is in progress. Data were acquired at 1 second intervals on 20 m spaced lines. The new ground data were compared to recently-acquired, high-resolution airborne magnetic data and the ground data reveal significant additional details which have been incorporated into exploration interpretation and 3D models including potentially mineralised structures some of which will are being tested by drilling.

A confidentiality period exists with Kirkland Lake Gold regarding the study results. Joseph has accepted a 2020 graduate position with RioTinto in Perth.

Environmental geophysics

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Welcome readers to this issue's column on geophysics applied to the environment. This month, I present an article by Geoscience Australia (GA) geoscientist Yusen Ley Cooper, on recent performances of EMusic – a project started by Antonio Menghini, a geophysicist working with the Aarhusgeo group in Italy.

As many of you know (and would have heard if you attended the dinner at the last AEGC) Antonio has been converting EM data into music for years now – see my initial introduction to this work in *Preview* **192** (February 2018). Antonio has been working with a group of jazz musicians from Italy who interpret some of the sounds that our geophysics inspires.

Here is the latest instalment of their story (many thanks to Yusen and others who are championing these efforts).

EMusic returns to Australia

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As part of Geoscience Australia's efforts to strengthen the public's appreciation for Earth science by making it more accessible, GA's Chief Scientist Steve Hill, in conjunction with Marina Costelloe from ASEG's diversity branch, sponsored and promoted "Sounds of Australia's Geology" – a concert based on Electro-Magnetic music.

EMusic is a project that started as an idea shared by geophysicist Antonio Menghini and musician Stefano Pontani, who established a procedure for transforming geophysical signals (time-domain data) into musical notes (Menghini and Pontani, 2016; Duncombe, 2019, www.emusic.world). Through this procedure, electromagnetic measurements of the subsurface are translated into musical notes. The transformation creates a natural soundtrack that reveals the geological composition of the subsurface at each location where the data was acquired.

The project has gained worldwide interest. Talks and live performances have been presented and supported by many scientific institutions and several societies like the EGU, ASEG, GA, USGS, and INGV. A paper covering the latest EMusic events will be presented at the next AGU Centenary Fall Meeting. The EMusic project is a vehicle which is used to expand people's perceptions of the landscape and geology through sound and live performances. Recently, jazz and electronic musicians like Enrico Rava and Francesco Cafiso have joined EMusic to play some of Earth's electromagnetic responses.

The band (Stefano Pontani – guitars and loops, Riccardo Marini – electronics, Marco Guidolotti – saxophone) and Antonio Menghini teamed-up with GA geophysicist Yusen Ley-Cooper and a

Figure 1. *Antonio Menghini, musicians Riccardo Marini and Stefano Pontani, GA's Chief-Scientist Steven Hill, Anna Maria Fioretti from the Italian embassy , musician Marco Guidlolotti, GA's scientists Sean Chua, and Yusen Ley Cooper.*

scientist-artist Sean Chua to perform a short snippet of "Sounds of Australia's Geology" at the recent 2019 Australasian Exploration Geoscience Conference gala dinner held in Perth.

The team worked on composing EMusic pieces by sonifying extracts from several of GA's airborne electromagnetic (AEM) datasets, some from AusAEM the world's largest airborne EM survey (http://www.ga.gov.au/eftf/minerals/nawa/ausaem). AEM surveys have traditionally been collected to underpin mineral exploration, agriculture and environmental resource management. GA was delighted to find new and innovative ways of using its AEM data, and to broadly communicate the importance of the science and research coming out of these geophysical datasets.

The audience who attended the Sounds of Australia's Geology concert, held in the Sir Harold Raggatt Theatre at Geoscience Australia, enjoyed a full visual and audio performance (Figures 1 and 2). The audience learned about geophysics, geology, remote sensing and musical structures through scales, chords and improvisation. Brief descriptions of contextual geology and the *in situ* geophysical responses followed the musical pieces from locations in Figure 3.

The first track of the concert showed the sonification of AEM data collected over the Yilgarn craton. It was an introductory piece that was arranged as a composition of "pure" EMusic (i.e. the simple sonification of the EM data direct to its mapped chords, without any involvement by the musicians). The execution times of the pitches are strictly linked to the acquisition times of the TEMPEST gates, provided that an expansion time of 1 million was applied in order for the single pitches to be heard.

A representative example of an AEM sounding from the Yilgarn/Albany-Fraser orogeny, in the proximity of the Tropicana deposit is represented in Table 1. The table shows the relationship between the Earth's response measured in femto Teslas, and the audible frequencies, i.e. the musical notes. Each note is paired with one of the 15 sampling windows used in the TEMPEST system. Each window probes simultaneously deeper into the ground, until eventually the EM signal is defused and turns into noise, in this case, after window 13.

Figure 2. *The band performing Sounds of Australia's Geology at Geoscience Australia.*

The second half of the first track has a reversed travel, hence going from the deepest layers toward the surface. During this track, the saxophonist Guidolotti began to interplay with the "pure" EMusic base, following the exact pitches and scales of the Yilgarn/ Albany-Fraser orogeny.

The performance continued to explore the concepts of geological formations and time across the four landscapes selected by Dr Yusen Ley-Cooper, showing peculiar moods, in some way reflecting the region's features.

Figure 4 shows an example of how the link between the EM data and music is achieved. In this case, the EM sounding was taken from a data set flown over the Menindee Lakes. The response was grouped and then split into three parts that are associated with different layers. The first layer, named "Sand Dunes", is based only on two pitches, and related to the thin and resistive features of this shallow formation. In contrast, the high conductivity of the "Blanchetown Clays" in the second layer allowed the capture of many more pitches, which have a chromatic cadence, following the slow

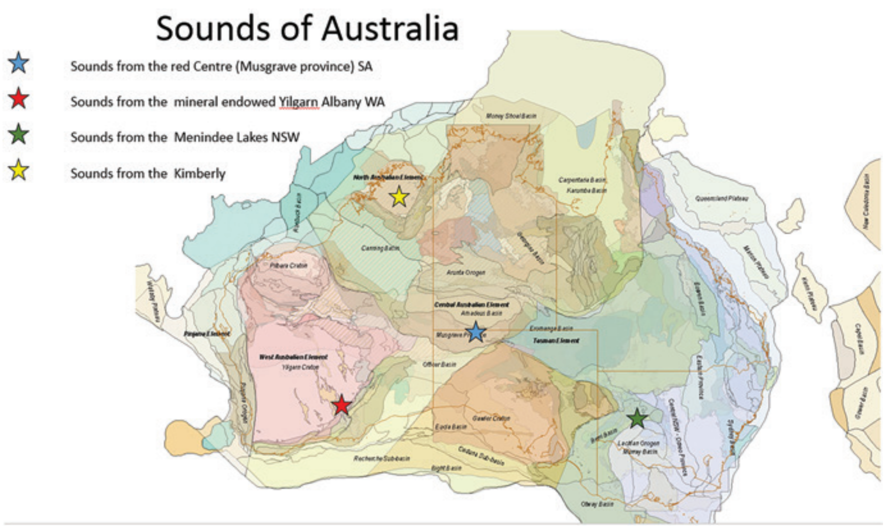

Figure 3. *Locations around Australia with AEM coverage; the Kimberly, Menindee Lakes, the Red Centre, and the mineral endowed Albany-Fraser/Yilgarn, selected for EMusic sonification, presented at the Sounds of Australia's Geology concert.*

Table 1. Transformation of an EM response to musical notes. A representative sounding in the proximity of the Tropicana deposit in the Yilgarn/Albany-Fraser orogeny. Each Musical note is scaled to sampling windows, probing simultaneously deeper into the ground before the EM is totally defused and an eventually goes into noise after window 13.:

fT (EM groundresponse)	MIDI	Freq	Notes_Min
8.74211	101.6435428	2.90E + 03	F#
7.63924	100.2818664	2.68E + 03	E
6.74863	99.03020026	2.49E + 03	Eb
5.79911	97.49907233	2.28E + 03	Db
4.49592	94.92892583	1.97E + 03	B
3.10849	91.20263002	1.59E + 03	G
1.85606	85.99556419	1.17E + 03	D
0.958532	79.32308352	7.99E + 02	G
0.439447	71.44822302	5.07E + 02	B
0.184508	62.685408	3.06E + 02	Eb
0.071028	53.04619098	1.75E + 02	F
0.019979	40.23865791	8.36E + 01	E
0.001905	16.50762678	2.12E + 01	E

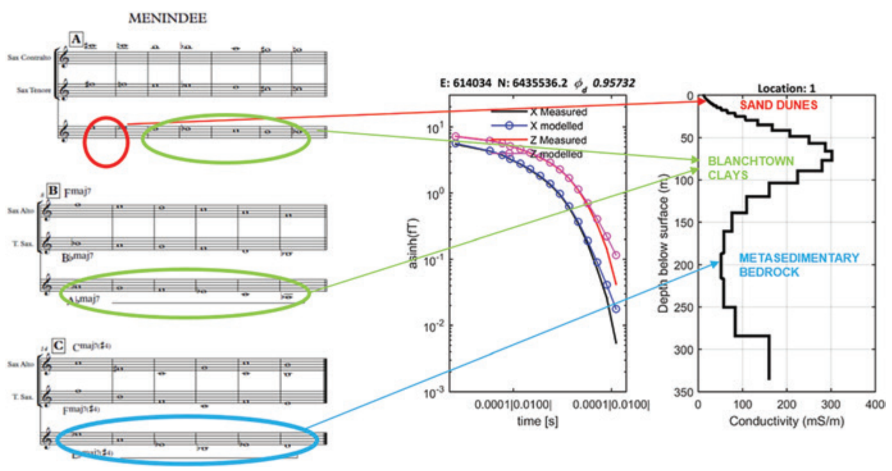

Figure 4. *Sonification of an AEM sounding from the Menindee Lakes.*

voltage decay. Finally, the third deeper layer, "Metasedimentary Bedrock", is based on the latest EM instrument's time windows. In this case, the lower conductivity range produced fewer pitches separated by wider intervals of silence.

In some of these regions, access to water is fundamental, and scientific data helps to understand aquifer architecture, groundwater quality and recharge. This concert highlighted the potential of scientists to more broadly promote and show their research by turning it into music and visual art. A full video of the concert can be found at https://www.youtube.com/playlist?list=PL0jP_ahe-BFIDEnLczascdDTAGIjWQiHi.

Dr James Johnson Geoscience Australia's CEO described the event as "Music from the red centre … an extraordinary experiment at Geoscience Australia, in collaboration with the Italian Embassy. Wonderful Italian musicians playing music derived from the electromagnetic signals of the Earth's crust in central Australia, listening to the Earth".

The short Down-Under tour finished in a small jam session with Canberra local jazz musicians at a neighbourhood cafe.

Acknowledgements

Geoscience Australia and ASEG's diversity branch sponsored this concert. Without their support this event would not have been possible. We also would like to thank the Embassy of Italy for the assistance they provided, and would particularly like to recognize the work of GA's Communications and Media team.

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Minerals geophysics

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Geophysical advice

If you're in the mineral exploration business, how does geophysics function in your organisation? Do you have your own dedicated geophysical group, do you rely entirely on external consultants, or is it a mix, say in-house for routine geophysics and outside specialists for something out of the ordinary? And what about the geophysical surveys themselves? Do you undertake these yourself using in-house and/or rental equipment, do you always use geophysical contractors, or is it a mix, perhaps determined by your in-house expertise and capabilities?

In the "old days" (1960s – 1980s), most major Australian and international mining companies had a large in-house exploration group, which incorporated a substantial geophysical section often with the capacity to carry out routine ground magnetics, gravity, radiometrics, electromagnetics and IP-resistivity surveys using in-house personnel and even in-house equipment. In part this was a reflection of the paucity of locally experienced geophysical contractors (particularly in Australia in the early days), in part it was considered desirable from a cost advantage and quality control viewpoint and for timely access to crews and equipment, and in part it was a reflection of the need to keep perceived superiority in methodology confidential for commercial advantage. Some exploration groups even undertook their own airborne geophysics, but normally this had to be entrusted to specialised contractors.

In "modern times" things have changed. Geophysical surveying has become much more sophisticated. There are specialised contractors out there with the expertise and equipment that you just don't have. Also, the appetite for complete in-house exploration capability has waned somewhat. In fact, within the majors, the appetite for exploration itself has waned. Some majors see purchase of advanced projects, often from junior explorers, as a better option than undertaking the exploration themselves, keeping only an overview team in-house to vet opportunities and supervise the technical aspects of joint ventures. And those majors who have retained in-house exploration teams prefer to have certain work contracted out rather than retain a large group of specialists. Cost control has become dominant and confidentiality in methodology is now more likely to be the preserve of the specialised contractor or consultant.

In junior exploration companies, the costs associated with having an in-house geophysicist may be prohibitive and the work load doesn't justify it. The small team size necessitates the use of external geophysicists on an as needs basis. There are now many very experienced geophysical contractors and consultants within the industry who provide exactly these services.

So, if you have access to geophysical expertise within your organisation, how do you actually use it? Do the geophysicists (in-house or external) concentrate only on geophysics in splendid isolation, or are they there merely to generate products for the geologists to use as they see fit? Geophysics done in isolation, no matter how technically brilliant, runs the risk of being out of touch with geological reality. Simply providing images and inversion models for geologists to use, no matter how well designed they are, runs the risk of geophysical results being used inappropriately.

The usage style I favour, as you might expect if you've read some of my previous pieces, is a bit of both. I see the geophysicist's role as two-fold - a mix of providing geophysical expertise at all stages of the exploration process, and of generating appropriate geophysical products to be used by geologists with geophysical guidance.

And are your geophysicists part of a remote specialised section in head office or are they on-site as an integral part of the exploration team? Geophysical survey planning, and processing, presentation and interpretation of the results can all be done remotely, with the final products conveyed using modern communication facilities. Do we really need geophysicists on-site?

I think we do, certainly at critical points in the exploration process. I'm old fashioned enough to believe that you can't beat face-to-face communication and interaction, particularly where an interchange of ideas will enhance the end result. Going one step further, I'm having second thoughts about the ubiquitous use of presentation software such as PowerPoint to convey ideas no matter what the situation. Are these presentations sometimes just too glossy and glib with an emphasis on the graphics themselves rather than the ideas behind the graphics? Do the audience miss the finer points? Sometimes standing around maps (yes, real paper maps), or drawing on a white board may be a more appropriate way of getting ideas across and having the team interact with the speaker and providing their own input.

So, the optimum exploration model may be to have geophysicists embedded within the operational team, interacting with the geologists on a daily basis at all stages of the exploration process, and providing both geophysical expertise and products for the geologists to use under geophysical supervision. Where the team size or workload doesn't warrant an in-house geophysicist, perhaps asking more of your geophysical consultant rather than the basic "here's the problem – do what is necessary" would produce more interaction and lead to a better result.

Seismic window

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Stratal slicing

Stratal slicing is a technique that fills the gaps between interpreted horizons in a 3D seismic volume. It is described on the SEG web site as a proportional or linear slicing between two or more reference surfaces in a seismic volume. The aim is to improve the understanding of otherwise unclear or muddled horizons. Many software packages will calculate the stratal slices and extract amplitudes at the press of a button but it is quite easy for those of us with deep pockets and short arms to do our own calculations (see box).

Calculating stratal slices

TWT (x) = TWT(A) + x (TWT(B)-TWT(A))/N

Where x is the slice number from 1 to N and N -1 is the number of slices between the horizons A & B

TWT is two-way time

Here is an example of stratal slicing in a simple setting in the Vulcan sub-basin of NW Australia (Figure 1). The geology appears quite simple with several continuous parallel reflectors. Three reflections (A, B & C) were picked across an area of interest and amplitude maps of these surfaces were quite boring with no obvious anomalies. The interval between A & B was divided into 10 layers while the B to C interval was divided into two layers using stratal slicing instead of picking each layer by hand or auto-tracking. Just below Horizon A is a reflector which has several points of high amplitude and polarity flips. Below that is a reflector that is broken up such that it would be tricky to interpret across a large area. A similar interval is present about midway between reflector B & C. Using stratal slicing, amplitude maps of each can be quickly produced in order to aid the geological interpretation of the area.

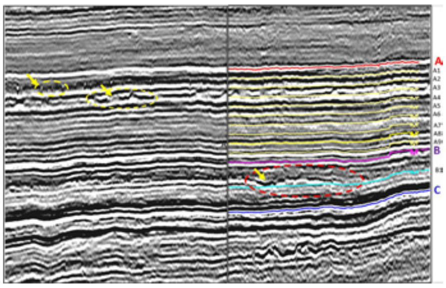

Figure 1. *Seismic line showing picked horizons A,B & C and nine stratal slices between A & B and one between B & C (right). Horizon overlays are removed (left) to show some anomalous features of interest in ellipses.*

Stratal slice A2 does indeed have several circular point features, perhaps dewatering mounds or debris from a meteor shower (Figure 2). These are difficult to see on the stratal slice amplitude map, so an RMS amplitude was calculated over the A2 to A3 interval to enhance the small circular anomalies (Figure 3). Layer A3 is quite different and more interesting with several quite regularly spaced incisions or channels crossing the area from northeast to southwest (Figure 4) and although the reflectors look similar the stratal amplitude at B1 has broader features trending north–south (Figure 5).

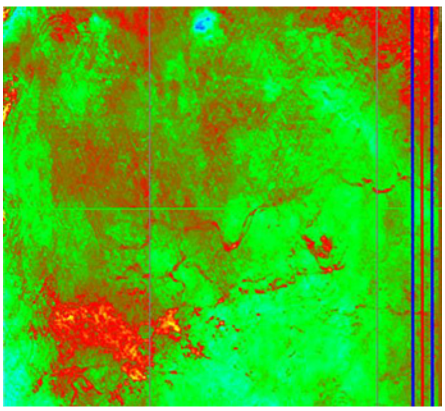

Figure 2. *Amplitude of stratal slice A2. The point features seen on the vertical section (Figure 1) are subtle red spots.*

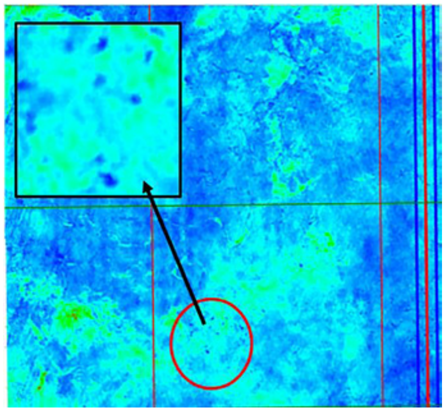

Figure 3. *RMS amplitude over the A2–A3 interval. The enlargement clearly shows the small circular features.*

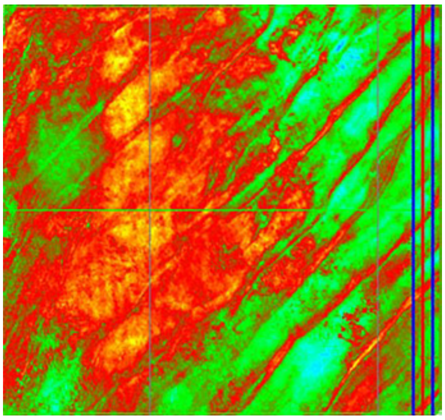

Figure 4. *Amplitude of stratal slice A3 showing several linear, equispaced, parallel northeast - southwest channels. There is a large change in geology between this slice and the slice immediately above (Figure 2).*

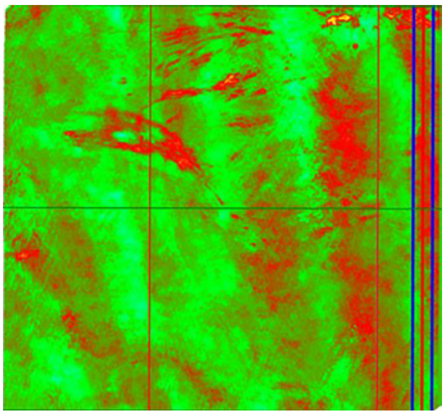

Figure 5. *Stratal slice B1 amplitude has several broad features trending north–south.*

Finally, congratulations to Tony Marsh of Chevron who was awarded the best oral presentation at the AEGC conference last September for his presentation about Stratal slicing.

Data trends

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A quick mineral petrophysics primer

When explorers download mineral petrophysics data from the Geological Survey of South Australia I am invariably asked "what are these numbers"? A fair point since magnetic susceptibility measurements (mag sus from here on) can be as confusing as an electricity bill, and specific gravity has its own oddities. This quick primer might help.

A simple explanation for mag sus measurements is that unpaired electrons emit magnetic fields, and in some molecules those electrons can be moved by outside magnetic fields. Susceptibility will be positive if the internal magnetic field aligns with the outside field. Why does this matter? It indicates how much of the geomagnetic field in a TMI map is amplified by this physical phenomenon.

Measurement of Specific Gravity (SG) relies on the Archimedes Principle; the ratio between weighing a rock in air versus weighing a rock in water. This reduces to the ratio of rock density to water density, and since water has a density of 1 (one), this leaves only the density of the rock.

Mag sus and SG measurements are both dimensionless quantities where the units cancel out. Divide a metre by a metre and you have a ratio instead of a measurement with a unit. Hence you will see NOUNIT listed for specific gravity. Magnetics has more glamour in physics so it gets the *SI*, the official dimensionless unit of the Standard Internationale, but you might find old logs with *cgs* (centimetre – gram – seconds system). The notable differences between the two systems:

- *cgs* uses the centimetre as the standard length instead of the metre
- *SI* uses different dimensions for the two magnetic fields susceptibility is comparing, and you need to multiply by 4π for the SI values
- *SG* often gives the equivalent density to gcm^{-3}, the cgs unit, and you might need to multiply by 1000 for the SI unit of kgm^{-3}

However, it is the numbers that are most confusing because of the order of magnitude of numbers displayed by different devices. Different conventions in displaying numbers with scientific notation have (sort of) taken hold between handheld (10^{-3}) and downhole (10^{-5}). Enough for the National Data Submission guidelines to expect either of those formats. But this is not a hard norm since the handheld GMS-2 and newer downhole logs claim the more accurate 10^{-6}. For those who are interested, MRIs use 10^{-7}.

For simplicity, it was decided by the GSSA that all mineral values be changed to their plain old values devoid of scientific notation. That meant moving the decimal point by dividing by the number of zeros (i.e. x 10^{-3} divides by 1000). As a rough guide, your resulting values should be within the range of the logarithmic graph in Figure 1 (0.00001 to 10 SI). Note this graph does not reflect a general rock population since magnetic sampling of core favours core from magnetic anomalies.

How this affects your software is debatable. It may treat the numbers as relative and generate equally valid ratios in the solution. It may assume an implied order of magnitude and accidentally treat uninteresting sediments as signs of haematite.

Some more tips under general topics:

Gauging the reliability of mag sus:

- Measurements over 1 SI in Figure 1 were taken from a magnetite core that resembled iron bars more than rock
- 20 is the theoretical maximum
- Note that zero is very common for metal free minerals
- Negatives are possible
- Do not take readings while the core is sitting in a metal tray

If the logs name the device, you can try to gauge the implied order of magnitude:

- Terraplus KT (5, 9, 10) meters are x 10^{-3}. The display is floating point, where the decimal moves while maintaining the order of magnitude on the display
- Fugro GMS-2 is opposite and changes orders of magnitude of the display so it can be a judgement call to work backwards with old logs

When in doubt, use the lithology logs:

- Sandstone/sediments 0.00001 – 0.0001
- Haematite 0.0001 – 0.01
- Haematite/Magnetite mix 0.001 – 0.01
- Magnetite dominate 0.01 – 10

(Now you can see why downhole loggers prefer using scientific notation)

Quick points on specific gravity:

- Accuracy is limited to tenths of a gram at best
- Density should increase with significant increases in susceptibility

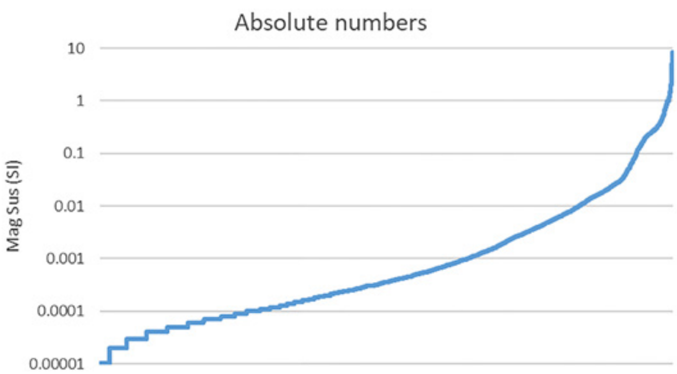

Figure 1. *A graph of open file magnetic susceptibility values taken from SA Geodata. Population was decimated to enable graphing in Excel. Logging favoured magnetic anomalies.*

Webwaves

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Web page auditing using Lighthouse

Recently the ASEG website was moved to a new server provided by AWS. This new server offers increased performance for a better browsing experience, coupled with more comprehensive monitoring and security. There are tools on the web that can be used to assess the performance of websites, and today we will look at one that is easy to use and available to the 64.92% of users who use Chrome as their main browser[1]. Similar tests can also be run by using utilities such as https://webpagetest.org/.

The Google Chrome web browser comes bundled with a comprehensive and open source utility for analysing and improving the performance of web pages. This tool, called Lighthouse is also available on Github at the following location: https://github.com/GoogleChrome/lighthouse

The Lighthouse utility is an automated procedure which takes an input URL and runs a series of audits on the local machine to generate information on the performance of a web page in a series of categories.

Running an audit

From the Chrome browser, open DevTools by pressing "F12" and select the Audits tab (Figure 1)

There are various categories that can be set for the audit. These include:

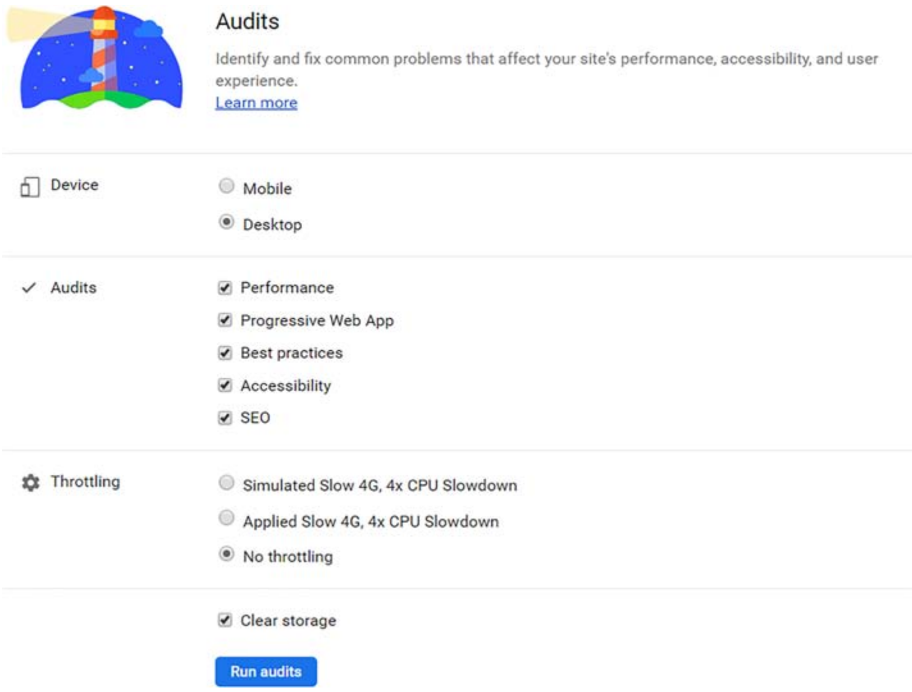

Figure 1. *Audits screen.*

- Performance – how long does this page take to show content and become usable?
- Progressive web app – does this page meet the standard of a Progressive Web App?
- Best practices – does this page follow best practices for web development?
- Accessibility – is this page usable by people with disabilities or impairments?
- SEO – is this page optimised for search engine results ranking?

Additionally, you can select whether the web page is being analysed as a desktop or mobile site and simulate throttling of CPU and network speed.

Now select "Run Audits" and wait less than a minute for the results to become available. After completing the audit, you will receive a score in each of the categories selected. Figures 2 and 3 show the scores from tests on the ASEG and SEG websites.

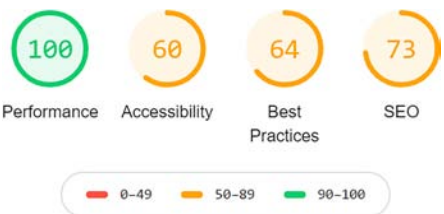

Figure 2. *Results from the ASEG home page.*

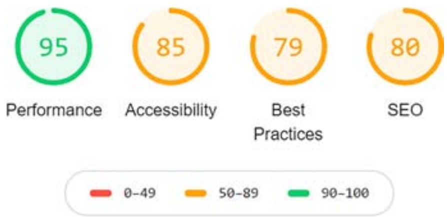

Figure 3. *Results from the SEG home page.*

Scrolling down through the results shows a breakdown of metrics, opportunities and diagnostics for each of the categories. These provide details of improvements that can be made, as shown in Figure 4, for the performance tab of the ASEG website.

Here, the new server is providing a great level of speed, helped along by a fast internet connection. Detailed under the opportunities tab is the suggestion to serve images in next-gen formats to be web friendly. A lot of the images on the ASEG website are sourced from the photo competitions, and have not yet been reformatted to suit the web.

The Accessibility score is the lowest score on the ASEG website and reflects the ability of users with an impairment or disability to access the website. It is worth noting that this includes people that do not identify as having a disability

[1] https://gs.statcounter.com/browser-market-share#monthly-201910-201910-bar

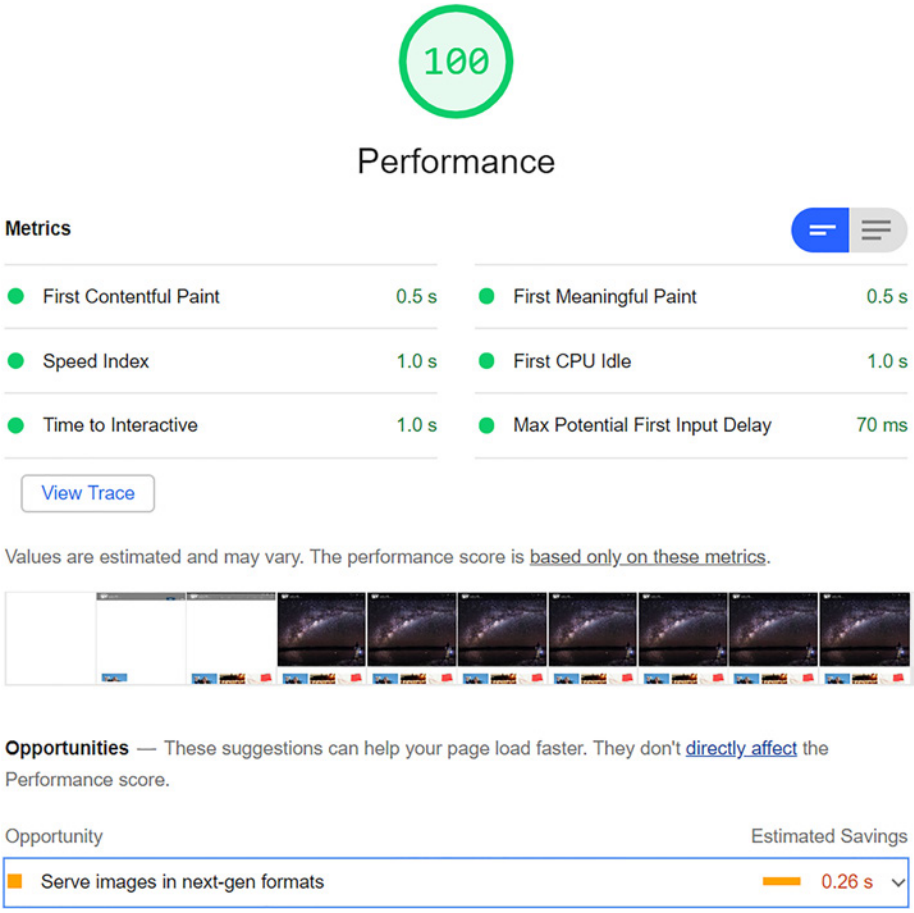

Figure 4. *Details of suggested improvements to the ASEG website.*

such as those using older devices, those without fast broadband, older users, or simply those in poor lighting conditions. This is important to our Society as the number of retired members doubled from 2014–2018. Guidelines exist with recommendations for meeting the needs of ageing web users[2]. The WAI also have a business case for accessibility[3], which highlights the advantages of making digital resources accessible.

Some web pages on the ASEG website require improvements to usability and accessibility for all users. These include the publications pages which are currently requiring a major overhaul. By the end of 2019 an improved version of these pages will be available. The current methodology of accessing Member only publications will persist – with authentication coming from logging on through the ASEG website. Additionally, the contractor database is in the process of being updated to include a map view and tags to improve searching. The website has also been updated with an interactive map showing the location of geophysical test ranges (Figure 5).

If you have any suggestions for improvements to the website, please get in contact via email webmaster@aseg.org.au, or fill in the contact page on the website.

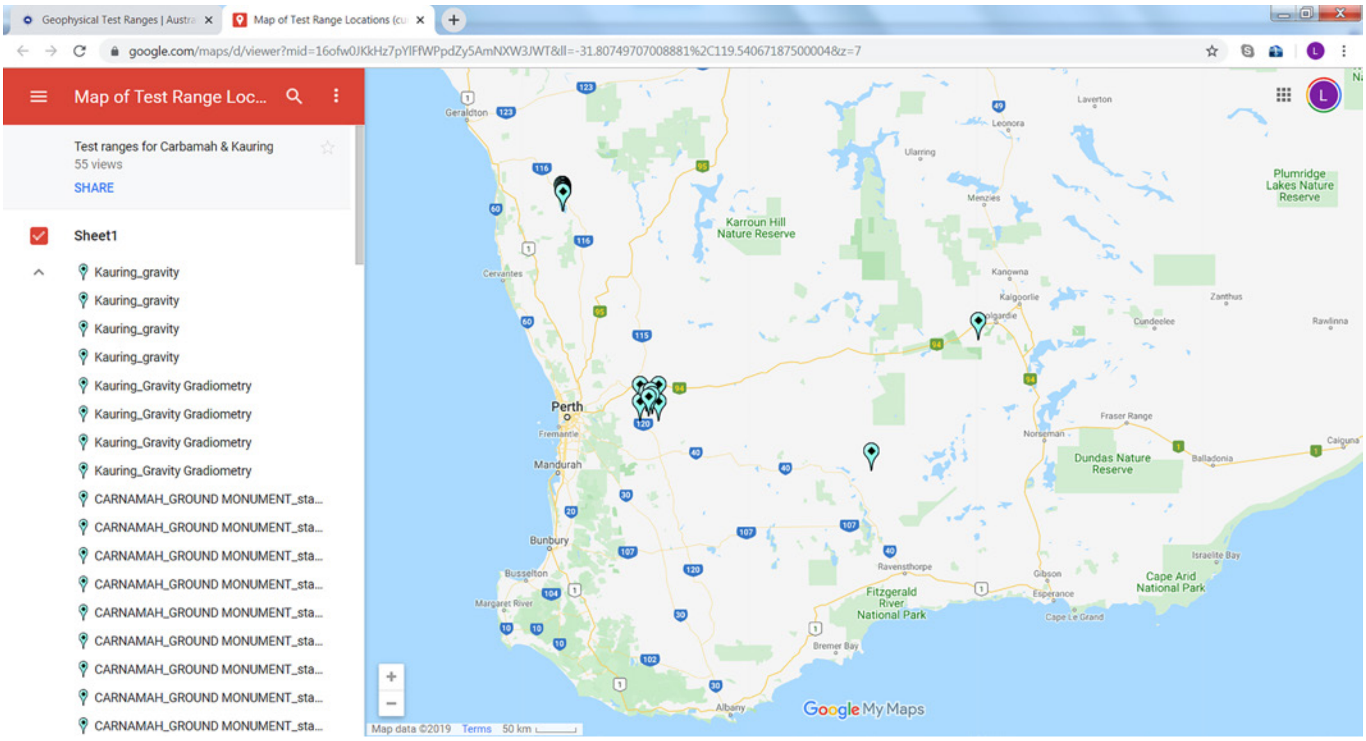

Figure 5. *Thanks to Tom Zhao, the ASEG website has recently been updated with an interactive map showing the location of geophysical test ranges in Australia. To check it out go to https://www.aseg.org.au/technical/geophysical-test-ranges.*

[2] https://www.w3.org/WAI/older-users/
[3] https://www.w3.org/WAI/business-case/

Pyrite – the firestone

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Introduction

Non omne quod fulget est aurum

This medieval Latin caveat was used by William Shakespeare in 1596 in the Merchant of Venice (Act 2, Scene 7): and by Miguel de Cervantes in 1615 in his Don Quixote (Part 2, Book 3).

All that glisters is not gold

So true. And, in nature, as geoscientists know, a lot of the glittering is done by pyrite "fool's gold". But it is far from being a material worthless to humankind. Indeed, this sulphide itself often contains gold.

Bright, brassy, brittle, ubiquitous pyrite is the most common sulphide. Cryptocrystalline to coarsely crystalline, it crystallises over a wide temperature range and manifests many forms: cubes (with or without striations), prisms, octahedra, pyritohedra (irregular dodecahedra with five sided faces), and granular (no recognisable external isometric features, but the internal structure is cubic). Aggregates of crystals or grains can form nodules, radiating suns, or bars (crystals stacked in one direction). It manifests as disseminations, veins, or massive deposits in igneous, metamorphic and sedimentary settings. Its presence can be boon or bane. Pyrite may be a guide to metallic mineralisation, or, owing to its included gold content, may be economic mineralisation by itself. Pyrite may obscure indications of valuable mineralisation, or pose severe environmental problems in land use. Most geoscientists, in the terrains they investigate, encounter and deal with pyrite sometime, or many times, in their careers.

Pyrite occurs in many modes, from nanocrystalline dust in recent sediments to truly colossal lenses of solid pyrite, associated with quartz porphyries and Palaeozoic slates, in the Rio Tinto deposits of Huelva Province west northwest of Seville, Spain. Here pyrite has been open cut mined for millennia as a source of sulphur (by roasting), and for its included gold. Copper from the chalcopyrite also present. In the huge, low grade, auriferous, carbonate hosted Carlin style mineralisation, gold occurs along with mercury, arsenic and antimony as surface coatings on, and fracture fillings in, disseminated pyrite of extremely fine grain size. Australia has many impressive massive pyrite deposits such as those at Mt Lyell, Nairne, Koolyanobbing, and Norseman. Pyrite in less concentrated form pervades the Australian geological scene. It is a persistent mineral below the oxidation zone. Pyrite, its presence, and its physical properties, are very relevant considerations in hard rock, soft rock, engineering, environmental, and hydrology geoscience investigations. It also has a very interesting history.

Rickard (2015), in an outstanding book, comprehensively documents the general science of pyrite, its benefits, and its problems. For the mineralogist or mineral collector, Voynick (2011, 2018a, 2018b) and Jones (2016) provide good guides to pyrite's occurrences and history. Lindgren's (1933) classic text still furnishes useful information on pyrite deposits. Deer, Howie, and Zussman (1992) summarise pyrite's mineralogical features.

This article reviews, quite subjectively, selectively, and discursively, some of pyrite's history, and presents experimental data to shed a little light on a somewhat ambiguous aspect of pyrite's physical properties – its conductivity.

A summary of pyrite's main properties is given in Table 1. Herein, pyrite refers to the cubic sulphide FeS_2; pyrites is used as the umbrella term for a collection of yellowish metallic sulphides, see Table 2. Note that marcasite is pyrite's unstable low temperature dimorph. Marcasite is a pyrites, it is not pyrite.

Three forms of pyrite are shown in Figure 1.

Fire

Humankind's development was facilitated by agriculture, the wheel etc. Predating all this was fire, without which progress would have been impossible. This was appreciated by the rogue Titan demi-god Prometheus ("careful foresight" in ancient Greek) who is said to have fashioned man from clay and to have furnished him with fire (*pyr* Gk.). The fire was in the form of sparks inside a plant stem stolen from Olympia. This infuriated the boss-god Zeus, who punished Prometheus by chaining him to a rock on Mt Caucasus where an eagle incessantly pecked his innards. So sad, such suffering, but at least, in this mythical version, people had fire. Access to fire for early humans whether by Prometheus' spark, a forest fire ignited by lightning, or a burning flare of natural gas venting from a fissure, was not much use because such sources were not portable as hunter-gatherers moved around.

Pyrite, which sparks under percussion, provided portability (until the Iron Age). Mastery of fire happened perhaps hundreds of thousands or more years ago (the subject is controversial). It was the great instrument of change. Cooking plants and flesh rendered them safer and easier to digest, so a wider range of foods became available. Smaller digestive systems and larger brains evolved (Wrangham 2009). Fire extended the day. At night, fire kept big bities at bay. Around the hearth, or campsite, efforts to express opinions and relay information would

Table 1. Pyrite: summary of properties.

Synonyms	Pyrite, iron pyrites, common pyrites, mundic, fool's gold
Colour, lustre	Brassy yellow, metallic splendent lustre – pyrite has a very high light reflectance
Chemical Formula	Fes_2 (46.6% Fe, 53.4% S): $Fe^{++}(S_2)^{-}$
Molecular Structure	Face centred cubic: Fe atoms occupy the corners and centre faces of cube; S pairs (dumb bells) occupy mid points of cube edges and the cube centre [see Fig.4.7, Rickard (2015)]; covalent bonding of Fe and S
Stoichiometry	Nonstoichiometric: mineral and trace element inclusions are common, and significant
Oxidation	$2FeS_2+7O_2+2H_2O \rightarrow 2H_2SO_4+2FeSO_4+260kJ/mole$, in the presence of oxygen and moisture an exothermic reaction occurs → heat + sulphuric acid + ferrous sulphate which when hydrated is the mineral melanterite $FeSO_4 . 7H_2O$ (density ~1.85g/cc) Gottschalk and Buehler (1910) note other possible oxidations of pyrite producing sulphur, sulphur dioxide, and hydrogen sulphide
Density	5.02g/cc, can vary
Moh's hardness	6-6½, very hard but less than flint or quartz, 7
Magnetic volume susceptibility	$\leq 4 \times 10^{-5}$SI, a weak paramagnetic
Electrical conductivity	Nominally ~1000 S/m but can vary considerably depending on texture and semiconductor type (p, n)
P wave velocity	~8.10 km/s, very high
S wave velocity	~5.18 km/s
Poisson's ratio	0.15, low
Young's modulus	304.8 GPa, very high for a mineral and indicative of stiffness – pyrite is brittle and not ductile
Thermal conductivity	≥20 W/m/°K [quite high, compare feldspar, quartz 2, 8 W/m/°K respectively]

Note: Sulphur (S, 2.1g/cc) amounts very approximately to 0.1% of the earth's crust; most of this occurs in iron sulphides, chiefly pyrite. Iron amounts to ~5% of the earth's crust and occurs widely in silicates, oxides and sulphides.

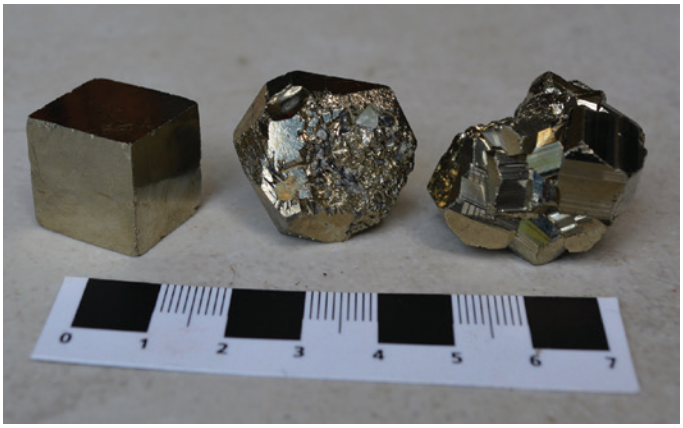

Figure 1. *Pyrite crystal cube (lacking striations) from Logrono Spain, left; one pyritohedron crystal from Arusha Tanzania, middle; aggregated striated pyritohedra from Huallanca Peru, right.*

surely have contributed to the development of language. So, intelligence flourished. Members of early human groups carried a compact strike-a-spark ignition kit comprising a nodule of pyrite (Moh's H=6) held in one hand, a rounded rod or piece of harder stone such as durable flint (H=7) held in the other hand (Figure 2), and tinder (dried vegetation) – all could be placed in a leather pouch (Voynick 2018a). Nodular pyrite (Figure 3) has a radiant texture and an irregular surface conducive to optimum shattering and sparking. A fist-sized, coarsely crystalline cube or pyritohedron (or aggregates of them) are not suitable for fire striking. If pyrite and flint were not available by collecting or trading then recourse was had to the frictional wood-on-wood technique.

A piece of pyrite has a passivated surface in its natural state i.e. it is shielded by the adsorption of oxygen, hydroxyls and the like held on its surface by van der Waal's forces and dangling bonds on the ridges of its micro-rugosity. This results in layers, a few molecules deep, which impede or prevent pyrite oxidising. Pyrite is brittle (Table 1) with a pronounced conchoidal fracture producing sharp fragments. When struck, imparted kinetic

Table 2. Pyrites (collective term for yellowish sulphides): selected pyrite and pyritic samples.

Name	Colour (shades of yellow)	Formula	Crystallinity	Hardness (Moh scale)	Density (g/cc)	Conductivity
Iron pyrites PYRITE	Bronze yellow to pale brass yellow	Fes_2	Cubic	≤6½	5.0	Varies
White iron pyrites MARCASITE	Pale bronze yellow	Fes_2	Orthorhombic	≤6½	4.9	Low
Arsenical pyrites ARSENOPYRITE	Silver white – pale copper tarnish	Fe As S	Pseudo orth.	≤6	6.1	Low
Copper pyrites CHALCOPYRITE	Brass yellow	$CuFeS_2$	Tetragonal	≤4	4.2	High
Magnetic pyrites PYRRHOTITE	Reddish-brownish bronze yellow	$Fe_{1-n}s$ ($n \leq 0.2$)	Monoclinic (magnetic) & hexagonal varieties	≤4½	4.6	Very high
Capillary pyrites MILLERITE	Pale brass yellow to bronze yellow	NiS	Hexagonal	≤3½	5.5	Very high

Notes:

- *cited data from various sources, approximate only*
- *marcasite is a low temperature unstable diomorph of pyrite*
- *pyrite and arsenopyrite commonly associated with gold deposits and these minerals can host blebs of gold in their own structure*
- *conductivity qualitative indications: low = 100's S/m or less, high = 1000's S/m, very high = 10,000's S/m or more*
- *for pyrite's conductivity ranges see Table 3 (limited data set)*
- *metallic lustre sulphides only in this Table e.g. orpiment, As_2S_3, a soft lemon yellow mineral is not included*
- *pyrite is the sulphide with the highest exothermic oxidation and best sparking; marcasite also sparks, as does arsenopyrite (accompanied by a garlic odour)*

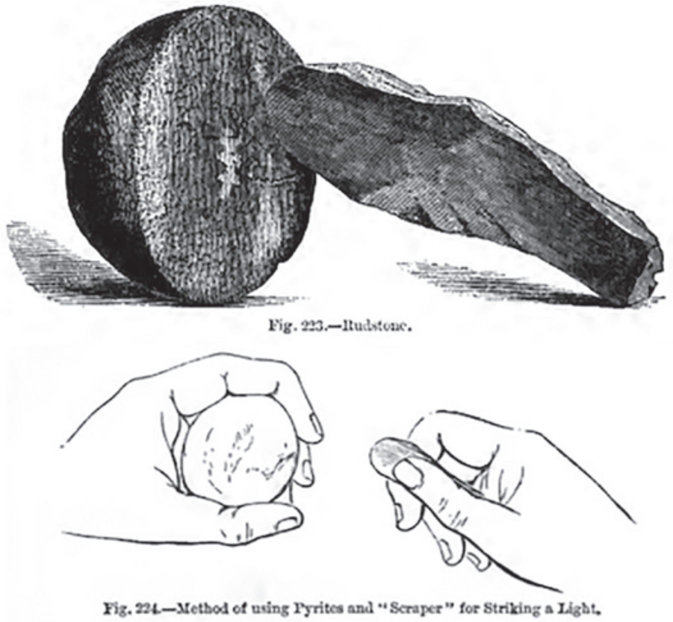

Figure 2. *Fire making implements from a Bronze Age burial site in Scotland (sketched by Evans 1897) used about 5000 years ago to ignite tinder. The hand held pyrite nodule hemisphere is struck with the flint bar to generate hot sparks.*

Figure 3. *A fine to medium grained pyrite nodule such as the sample from Hunan China (left) easily generates good sparks when struck by flint, quartz, or very hard steel, but the coarse grained lump of Peruvian pyrite (right) does not.*

Figure 4. *Ötzi man was recovered in 1991 from a glacier in the Austro-Italian Alps. Over 5000 years ago this shepherd used pyrite and flint, found on his person (reconstructed here), to make fire. Ötzi man reconstruction /https://commons.wikimedia.org/wiki/File:Oetzi_the_Iceman_Rekonstruktion_1.jpg/ CC BY-SA 3.0*

energy warms the pyrite (the heat mainly dissipates) and dislodges tiny fragments with fresh faces and very reactive sharp edges which are not passivated and react exothermically with oxygen and moisture in the atmosphere (see equation, Table 1). Suitable tinder is ignited by a shower of rapidly oxidising, very hot, clearly visible sparking particles.

The glacier entombed mummy of a man who lived ~5000 years ago was found in 1991 in the Ötztal Alps of southeast Austria (Figure 4). This late Stone Age/early Copper Age man carried a flint knife, a copper axe, and pieces of flint and pyrite for percussive fire-making.

Pyrite in the ancient and medieval world

Pyrite was recognised as an iron sulphide by German mineralogists in the early 1700s. Before that, it was a collective noun for yellowish metallic sulphides (Table 2). Hoover and Hoover (1950) in their translation of the 1556 edition of the German George Agricola's monumental *De Re Metallica* remark in a Book 5 footnote:

The subject of pyrites is a most confused one; the term originates from the Greek word for fire, and referred in Greek and Roman times to almost any stone that would strike sparks. By Agricola it was a generic term in somewhat the same sense that it is still used in mineralogy, as, for instance, iron pyrite, copper pyrite, etc. So much was this the case later on, that Henckel, the leading mineralogist of the 18th Century, entitled his large volume Pyritologia*, and in it embraces practically all the sulphide minerals then known*.

The cubic mineral pyrite, FeS_2, is so spectacular in its splendid crystalline form that it easily draws the attention of a casual observer. It is not uncommon and it presents quite a contrast to the average drab, dun appearance of most rocks. It is rather odd that pyrite seems never to have been directly and

unambiguously described in the western world's surviving writings from antiquity and the Middle Ages.

Pyrites is discussed by Pliny the Elder (AD 23-79), admiral, administrator, naturalist. This prolific Roman author wrote the 37 books of his *Naturalis Historia (NH)* before dying, indefatigably inquisitive as ever, investigating the eruption of Mt Vesuvius which buried Pompeii and Herculaneum on the bay of Naples. Pliny, *NH*, 36, 137 (Eicholz 1971):

> *Molarem quidam pyriten vocant quoniam plurimus sit ignis illi sed est alius spongiosior tantum et alius etiamnum pyrites similitudine aeris. in Cyypro eum reperiri volunt metalllis quae sint circa Acamanta unum argenteo colore alterum aureo. cocuntur varie. ab aliis iterum tertiumque in melle donec consumatur liquor ab aliis pruna prius dein in melle ac postea lavantur ut aes. usus eorum in medicina excalfacere, siccare, discutere, extenuare et duritias in pus vertere. utuntur et crudis tusisque ad strumas atque furunculos*.
>
> Some describe the millstone as pyrites on the grounds that there is a lot of fire in it, but there is another pyrites that is similar, only more porous. Yet again there is another which resembles copper. They maintain that it is found in the mines near Acamus in Cyprus, one type of silvery colour, the other golden. It is roasted in various ways. Some roast it two or three times in honey until it is no longer fluid. Others firstly roast it on hot coals and then in honey. Afterwards it is drenched like copper. Medical uses of pyrites include heating, drying, tissue shedding and thinning, to transform hardened tissue into dischargeable matter, and raw and ground-up, to treat tumours and unsightly swellings.

Mediterranean millstones of the ancient world were often made of lava previously erupted from fiery volcanoes. Some lavas have considerable porosity. To the ancients, fire was the most dynamic and powerful of the four elements; the other three being earth, water, and air. Philosophers believed that the interactive agency of the four elements could explain nature; such beliefs persisted to the 1600s. So lava was regarded as having a fiery quality, hence pyritic.

Cyprus massive sulphides are a recognised metallic ore model (Cox and Singer 1986). Here large massive pyrite lenses, set in pillow basalts, host minor chalcopyrite (*et al*., including gold). So it seems that Pliny is, more or less, identifying (but not describing) pyrites as a material comprising pyrite and chalcopyrite, but his interest in it is purely medical. Doubtless ore processing in antiquity resulted in some sulphur being produced and used for medical purposes; sulphur still plays an important role in modern pharmacy.

Pliny continues *NH* 36,138:

> *pyritarum etiamnum unum genus aliqui faciunt plurimum ignis habentis. quos vivos appellamus, ponderosissimi sunt hi exploratoribus castrorum maxime necessarii. qui clavo vel altero lapide percussi scintillam edunt quae excepta sulpure aut fungis aridis vel foliis dicto celerius praebet ignem*.
>
> Some regard yet another kind of pyrites as having the most fire (power). Such stones are deemed "live", they are particularly heavy and are quite indispensable to those scouting campsites. When struck by a nail or, alternatively, by another stone, they emit a spark which, caught by sulphur or dry fungus or leaves, quickly provides fire, to order.

It appears that Pliny has pyrite in mind. The nail would need to be hard (like file steel), and the other stone would be flint, quartz, or quartzite.

Later he refers to a cubic mineral thought by some translators (but not this one) to be pyrite; Pliny *NH* 37,144:

> *Androdamas argenti nitorem habet ut adamas quadratis semper tessellis similis magi putant nomen inpositum ab eo quod impetus hominum et iracundias domet*.
>
> The man-taming stone "andromas" has the lustre of silver, like hard steel and always resembles squared-off pieces of mosaic stone. Learned Persians reckon that the name was assigned because it subdues the irascibility and passions of men.

Indeed. Surely a handy material for the modern day? What is it? Pyrite crystals can be cubic and they have a splendent metallic lustre. However the obvious adjectives *fulvus* (yellow) or *aureus* (golden) are not included in the description, rather silvery and steely are used (note: *adamas* can also mean diamond). Galena (PbS) is a more likely candidate. It has perfect cubic cleavage (whereas pyrite only has conchoidal fracture), silvery/steely colour, metallic lustre, and galena surfaces can display mosaic texture due to cleavage. Galena crystallises in cubes, cleaves to the faces of the cube, so its cleavage fragments are cubic. Some specimens easily disaggregate into small cubes when hit or even rubbed.

In the early Middle Ages, Marbod (1035-1123) was Bishop of Rennes, ~300 km WSW of Paris. Between 1061-1081, before the printing press, he compiled the first and most popular of all the medieval lapidaries with sixty minerals, gems, stones and their magical and medicinal properties, in 735 Latin hexameters. Marbod was popular for centuries. Beckmann (1799) gave a listing of the many editions and provided a complete Latin text, and commentary. Marbod's poem, *De Pyrite* has only four lines:

> *Cui fulvus color est, cui nomen ab igne pyrites,*
> *Se vetat astringi, pertractarique recusat.*
> *Tangi vult leviter, pavidaque manu retineri,*
> *Nam pressus nimium digitos stringentis adurit*.
>
> Pyrites derives its name from fire, its colour is yellow,
> it is not a good idea to grasp it tightly, it does not like to be fondled.
> Touch it lightly, handle it very carefully,
> for if you press on it too much it scorches your fingers.

Marbod is not much help either. The colour is right but the rest is admonitory imagination based on scraps of information from others. Marbod, doubtless, was aware of Pliny (*NH*), 37,189:

> *pyritis nigra quidem est, sed attritu digitos adurit*
>
> certainly pyritis (firestone) is ill-omened and what is more it burns the fingers when rubbed

Pliny's *pyritis* has never been identified.

It is clear that, in antiquity and in the Middle Ages, European natural science neither recognised nor understood pyrite as we know it, but it was a basic component of the pyrites group of minerals which were widely used. Societies in Asia and the Middle East also made use of pyrites, and Arab scholars knew pyrites as marcasite, but this will not be pursued here (see: Rickard, 2015).

Pyrite in the pre-modern and modern world

Pyrite continues to occupy a noteworthy place in social, industrial, mining, technical, and environmental matters.

Social pyrite

Pyrite is a cheap, common sulphide, and specimens of superb appearance are available. The variety of attractive forms, the brassy colour and splendent metallic lustre make pyrite an affordable favourite of mineral collectors. They seek individual crystals of striking appearance, and crystal stacks and clusters set in a matrix of other minerals such as quartz thus making attractive composite specimens.

Pyrite is also a gemmy ornamental material, but confusingly known as marcasite, an unstable dimorph which is quite unsuitable for this purpose. Pyrite when polished seems whiter than its usual colour. It is widely used in jewellery (Figure 5) owing to its low price (Liddicott, 1909).

Pyrite features in modern day lithotherapy. Pyrite crystals fit readily into the category of attractive diminutive objects not to be regarded merely as ornaments, but rather as sources of positive occult energies when worn as rings, necklaces or amulets or simply carried as pocket stones. If one believes New Age lore, then a hunk of pyrite placed on a conference table invigorates the ambience and optimises decisions – just the thing for a meeting to discuss exploration data? Furthermore, post meeting, the participants can be comforted by their own pet piece of pyrite which, we are assured by crystal therapists, helps breathing, circulation, brainpower, and promotes practicality, harmony, willpower. Perhaps the beneficial effects are due to a massaging of the vascular system by a thermal flux transmitted through the gullibility aether. However, this blood booster hypothesis seems to violate the second law of thermodynamics which does not permit the spontaneous flow of heat from a relatively cool (pyrite) to a warm body (37°C, human). Investigations continue into the fascinating topic of empowerment by pyrite, but the path is daunting, and strewn with credibility hurdles.

Figure 5. *A piece of marcasite jewellery. Marcasite itself is far too unstable for such a purpose. The marcasite is actually polished and faceted pyrite. The pyrite pieces are set in metal for this lizard brooch. https://commons.wikimedia.org/wiki/File:Marcasite_silver_lizard_brooch_2.JPG / Creative Commons Attribution-Share Alike 3.0 Unported*

Plato (427–347 BC) believed that the world had a soul and that the universe was alive and conscious. A strand of human philosophy, panpsychism, posits that materials can think, more or less, as consciousness is believed to be part of the fundamental nature of all matter. Mind is in all matter; all matter has experience (David 2016; Taylor 2019). Such a philosophical narrative is pregnant with possibilities. In the mineral kingdom consciousness could be the appreciation of the buzz and vibration of existence, if not the complex consciousness of humans. Who knows? One view asks why materials should not be conscious, and asserts that the denigration of panpsychism as loony is simply a manifestation of anthropomorphic bias. Pyrite has impressive physical properties (Table 1) and, being ubiquitous, could be regarded as an elite material, ideal for a consciousness study. What is it like to be pyrite? I glitter, therefore I am (apologies to Descartes). Socially committed geoscientists may find this weirdness a fruitful field of progressive research. It ticks the boxes for: atmospheric hygiene (no nasty carbon in its chemistry), diversity (it is decidedly different), inclusivity (the kinship of consciousness), and sustainability (there is so much of it). An environmental soft-print can be ensured by researchers eschewing vehicular and aeroplane transport for field work and conference attendance; bipedal motion, bicycle, scooter, canoe, ketch, and hot air balloon, are to be used instead. Samples for study would be ethically sourced and respectfully collected. The purity and potential of such a visionary project will attract plaudits, perhaps lavish funding. The result of these endeavours, in the current bracing climate of cultural relativism, would celebrate a non-normative conception of mineralogy. Cutting edge stuff, indeed, and an exhilarating opportunity for virtue signalling.

Pyrite mining

For centuries pyrite was the main source of sulphur until it was displaced by Frasch sulphur from the evaporitic caprocks of saltdomes, and more recently by scrubbed sulphur captured in the smokestacks of low emission coal power plants. However, pyrite is still mined for sulphur to a limited extent in China, Russia and India.

Most pyrite is now mined for its contained gold. These deposits are huge and low grade; the (sub) microscopic gold occurs within the pyrite, e.g. Carlin with 0.37% Au in arsenian pyrite.

Pyrite and alchemy

The dabblings and experiments of alchemy (Figure 6) up to the 18th century led to the development of modern chemistry which analysed and reinterpreted useful empirical data from the often obscurantist writings of early practitioners such as the great Sir Isaac Newton, who wrote over a million words on the subject. The old "chemistry" dealt with primitive pharmacology, chemical reactions and compounding, metallurgy, and the transmutations of base metals into gold. Aristotelian theory reigned: prime matter and forms interacted to produce the four elements fire, air, earth water which in various combinations accounted for all materials. Changing the proportions changed the material; any substance should be changeable into another substance under suitable conditions. Transmutation was the alchemists' ambition and pyrites encouraged continuing experimentations to achieve it for it was observed that pyrites could be converted into gold, even if the amounts were small. It is now well known that some pyrite deposits contain microscopic and sub-microscopic grains of gold, invisible to

Figure 6. *Pieter Bruegel the Elders' 16th century depiction of an alchemist in his laboratory doubtless spurred on in his dead-end endeavours by the recovery of gold from pyrite. But this was not transmutation, rather the chemical release and concentration of previously invisible gold. Pieter Brueghel the Elder - The Alchemist (1558, Ink on paper) Engraved by Philipp Galle / https://commons.wikimedia.org/wiki/File:Pieter_Bruegel_the_Elder_-_The_Alchemist.JPG / Public Domain*

the eye. Crushing and powdering this pyrite (known as pyrites to an alchemist) and then adding mercury causes the gold to form an amalgam which when heated vapourises the mercury and leaves visible gold. So pyrites could be changed to gold, seemingly corroborating the theory of transmutation and boosting hopes of converting base metals into gold if only the right conditions could be found. However, they never were. Many lives were spent, and fortunes lost, in these doomed pursuits.

Metamorphosis in the classical sense is the transformation of something into a new form, such as a human being turned into animal, vegetable, or mineral matter. Ancient and medieval cultures were imbued with the idea; it persists to the present day in religion, and fantasy movies. The Roman poet Ovid (43 BC – AD 17) relates some 250 instances of transformations in his *Metamorphoses.* The possibilities of transformation/transubstantiation/transmutation encouraged metal workers and many others to try to make precious metals from baser materials. They believed metals grew in the earth from an imperfect to a perfect state. Some expended enormous experimental effort to hasten the process by instantaneous transmutation. Others had a more leisurely approach such as the gold-panning Conquistadors in South America who threw lumps of platinum back into rivers to "ripen" into gold.

Pyrite – industrial chemistry

Most sulphide ores require roasting to obtain sulphur dioxide, SO_2, but pyrite has such a high sulphur content (53.4%) that in a pure and finely divided form it can maintain its own combustion without an external heat source.

For centuries pyrite was the main source of sulphur and sulphur dioxide used for bleaching, and in the manufacture of sulphuric acid, an important industrial chemical. Sulphuric acid applied to phosphate rock makes superphosphate for agriculture. In the clothing industries, pyrite produced the potassium aluminium sulphate alum indispensible in the chemical fixing of dyes to cloth. One recipe involves pyrite shales where the pyrite reacts with the aluminous clay content of the shales, and added wood potash, to give alum.

Pyrite provided an essential ingredient, sulphur, for a very dangerous industrial material: gunpowder. In the 13th century the German theologian Albertus Magnus documented gunpowder as a mixture of 2/3 niter (KNO_3 from soils and from pigeon and bat droppings in caves of arid regions) and 1/6 each of sulphur and charcoal. The pyrite-derived sulphur functions as an accelerant giving a bigger bang. The modern mix of 74.6% niter, 13.5% charcoal, and 11.9% sulphur gives an even better bang.

In the 1500s pyrite featured in the improvement of European weaponry, i.e. the facilitation of carnage wreaked on humans and animals. The hand cannon of the 1300s gave way to the slow, clumsy matchlock musket in the 1400s. The matchlock relied on a lighted match of saltpetre soaked hemp to ignite the gunpowder charge through a hole in the top of the musket barrel. It was cheap and, although hazardous, lasted until the 1700s. The projectiles from such weapons were able to penetrate the armour of mobile cavalry who could no longer efficaciously charge the infantry. The wheel lock pistol with a pyrite sparker ignition was developed for use by the aristocrats of the cavalry to fire at a distance on the ranks of the peasant infantry. It was an elite weapon with an ignition mechanism comprising a sprung, hardened steel, serrated wheel revolving rapidly against a piece of pyrite which ejected sparks into the powder pan of the weapon (Figure 7). It was simple, sturdy, reliable, and could be fired in an instant from horseback, but it was expensive so it was mainly used by the cavalry. Pyrite enjoyed a brief moment of military distinction, being a key component of a weapon which radically changed Renaissance battle tactics. It was replaced by the flint lock in the 1600s.

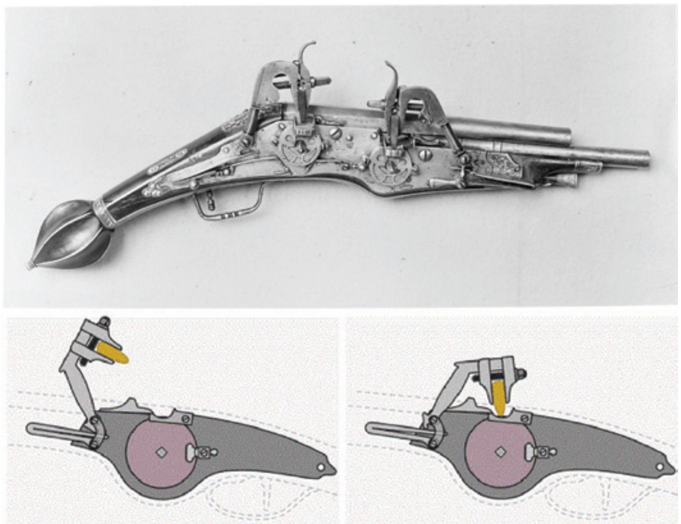

Figure 7. *A double barrel wheel lock pistol, beautiful but deadly. This type of pistol was fast and reliable, but expensive, and was used mainly by European cavalry in the 1500s https://commons.wikimedia.org/wiki/File:Double_Barrelled_Wheellock_Pistol_MET_2306.jpg / Creative Commons CC0 1.0 Universal Public Domain Dedication. The wheel lock ignition mechanism is shown underneath: when a sprung steel (H ≥ 7) wheel revolved rapidly against a piece of (yellow) pyrite, sparks were generated and detonated a gunpowder charge in the pan of a pistol. Prime position of the pyrite is shown on left; fire position is on the right https://commons.wikimedia.org/wiki/File:Wheellock_mechanism_(animated).gif / Creative Commons Attribution-Share Alike 3.0 Unported*

Pyrite and the environment; geohazards

Pyrite often occurs in coal as disseminations, coatings, and lenses. Such pyrite, when exposed, may be inert or reactive. If reactive it can rapidly oxidise in moist mine conditions. Reactivity depends on grain size and shape providing increased surface area of the pyrite and porosity for air to reach reactive sites on the pyrite (Beamish 2017). Under moist mine conditions such pyrite can oxidise rapidly producing iron sulphates such as greenish melanterite $Fe^{2+}SO_4.7H_2O$ (also known as copperas, green vitriol, iron vitriol). Fine acicular crystals of low density melanterite (1.9g/cc) readily mix with coal dust and, if inhaled, contribute to coal workers' lung disease (pneumoconiosis).

Potential acid sulphate soils occur in about 3 000 000 ha of pyritic Australian Holocene coastal floodplains. Pyrite is safely inert in the reducing conditions of its deposition, but oxidises on exposure to oxygen when the soil is disturbed by excavations involved in engineering infrastructure and agriculture (e.g. drains). The oxidation equations can be complex but are broadly summarised by the entry in Table 1. Oxidation of pyrite generates sulphuric acid; for each mole of pyrite that is oxidised four moles of acid are produced (Indraratna, Blunden, and Nethery 1999). Needless to say, this can have catastrophic environmental effects and requires careful assessment and management in affected areas.

Disseminated pyrite can cause problems in the construction industries using building stone, dimension stone, and rock fill (Ray 1988; McNally 1988; Smith 1999). Small amounts of pyrite can ruin an otherwise attractive stone. In building and dimension stone, such as granites and slates, pyrite oxidation generates rusty blemishes along fissures and on surfaces. In rock fill used for dams and embankments the presence of pyrite leads to pollution from mobile metals and acidic drainage. Alteration can be biochemical (Irdi and Booher 1994). Bacteria do occur in rocks. The bacterium *Thiobacillus ferro-oxidaus* converts pyrite to ferric ions and sulphuric acid. When the ferric ions further react with the pyrite a self-sustaining reaction can ensue. If calcite occurs with the pyrite, as in some roofing slates, gypsum is formed from the sulphuric acid with flaking and spalling.

Pyrite and technology

Pyrite has found applications in modern technology. Rechargeable lithium batteries have aluminium cathodes containing disseminated pyrite grains. Solar energy projects may find a use for semiconducting crystalline pyrite as a cheap photovoltaic absorber of radiant energy when sprayed in thin layers on exposed panels (Voynick 2018b).

Pyrite and early life on Earth

In sediments, a very common type of pyrite occurs as clustered microscopic aggregates. This is known as framboid pyrite. The accumulation of tiny pyrite grains has the appearance of a raspberry, and its formation is thought to be linked to anaerobic bacterial processes, such as the reduction of sulphates to sulphides, which have gone on for billions of years. The "iron-sulphur world" is a supposition of geochemists and biologists and is based on the premise that the origin of life required the active involvement of iron sulphides. These were ubiquitous even before atmospheric oxygen appeared, and acted as catalysts and conductors in biological reactions requiring electron transfer. Where would we be without pyrite? Rickard (2015) provides a full and lucid discussion of this fascinating topic.

Arid zone pyrite

In the field, pyrite in veins or in massive replacement bodies weathers and forms a limonitic capping i.e. a gossan (Blanchard 1968). Limonite is a general field term for a mix of haematite (Fe_2O_3), goethite $\alpha FeO(OH)$, and lepidocrocite $\beta FeO(OH)$. Alteration products of pyrite are frequently seen in arid areas in the oxidation zones of massive sulphides as cellular, spongy, boxwork structures which are developed through limonitic gossans which are ore indicators in economically mineralised pyritic sulphides. Pyrite often forms tough limonite pseudomorphs with the outline of the parent pyrite fully preserved (Figure 8). The replacement may be partial (a coating on the pyrite crystal) or it may be complete.

Pyrite – physical properties

Pyrite, FeS_2, has an intriguing set of physical properties for a ubiquitous mineral (Table 1). Compared to most minerals, it is quite dense, it manifests a very weak para-magnetism (unusual for an Fe compound), it carries a very fast compressional wave, it's Young's Modulus (a proxy for low ductility or stiffness) is extremely high, as is its thermal conductivity. All these make for a salient combination of characteristics that are, more or less, consistent for various pyrite occurrences. However another important property, perhaps of most importance to a geophysicist, is resistivity, (or its inverse: conductivity), and this is certainly not consistent. Thousands of resistivity measurements have been made on pyrite, perhaps more than any other sulphide. Most of these measurements have been on single crystals. Pyrite's resistivity, generally, is low, but it is quite variable and difficult to predict or anticipate in field work even if important factors such as mode of conduction, crystallinity, alteration, and texture are known. Information on pyrite resistivities can be found in Harvey (1928), Telkes (1950), Parasnis (1956), Hill and Green (1962), Parkhomenko (1967), Shuey (1975), and Olhoeft et al. (1981).

Pyrite is a semiconductor. Conduction can be n type (electrons) or p type (holes, actually electrons hopping into lattice holes and leaving holes in their wake). Trace or minor

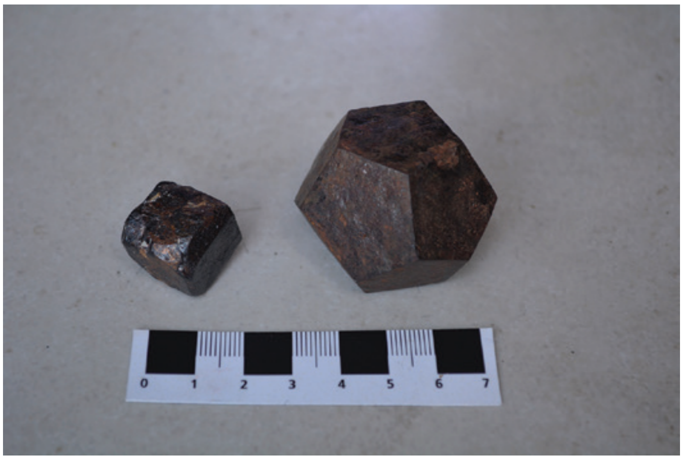

Figure 8. *Pseudomorphs of limonite, $FeOH.nH_2O$, after pyrite, result from extreme alterations in arid zones. The external features of the original cube (left) and pyritohedron (right) have been preserved. The cube is from Nilinghou South Australia, the pyritohedron is from Mkushi Zambia. Density for each is 3.7 g/cc, and mag k 110 x 10^{-5} SI. Both samples have very high resistivity, > 100 000 ohms.*

amounts of Cu, Co, Ni function as donors of electrons in n type, while As is the acceptor of electrons in p type. Note that arsenic can be quite common in pyrite environments e.g. as paragenetic white iron pyrites Fe As S. Shuey (1975) gives a modal resistivity of ~1×10^{-3} ohm m for n type, and ~3×10^{-2} ohm m for p type pyrite. The n type tends to be more conductive, but the p type seems to be more common. Despite the many measurements and investigations of Hall effect, Seebeck effect, chemistry, mineralogy, temperature dependence, and concomitant magnetic behaviour, it does seem that more studies are needed to understand better natural pyrite's DC and AC electrical behaviour, especially in aggregate rather than single crystal form.

It is interesting that pyrite has the useful electrical property (as does galena) of both p and n semiconductor types sometimes occurring in the one crystal (Shuey 1975). This resulted in pyrite's use as a detector in early radiowave crystal set reception circuits. A "cat's whisker" wire was used to probe the crystal surface until a suitable zone was encountered to fulfil the function. A p-n junction acted as a rectifier. The p type sulphide has no conduction electrons; the n type has no conduction holes. Holes and electrons cross the boundary making the p type more negative and the n type more positive. The application of a potential difference opposite to this interface polarity, a forward bias, gives a large current, but reverse bias decreases the current by orders of magnitude (this diode property of natural pyrite seems to have been little studied). In the radio circuit, virtually, only the positive part of the received alternating waveform is passed, thus achieving the rectification. The crystal detector circuit extracts an audio frequency (AF) signal impressed on the radio frequency (RF) carrier wave (now amplitude modulated, AM) picked up by the receiving aerial. This is connected to the primary of a transformer whose secondary provides input to the detector circuit (Figure 9). An early 1900s radio receiver was simply an aerial, the transformer, the pyrite detector (galena could also be used), and a pair of headphones in parallel with a couple of capacitors. The pyrite detector's function was to pass only the positive part of the incoming waveform and to produce a pulsating DC signal with RF and AF components. One of the capacitors was manually variable and was used to tune the incoming signal i.e. select the sender's frequency, the other capacitor sent the RF component to earth thus bypassing the headphones. The headphones were high impedance to maximise the voltage, and provided the listener with a sound similar to that used to modulate the carrier wave. No battery or other power source was required. Sensitivity was low, but adequate. All very simple and still used by hobbyists to this day. Pyrite was one of the key components in the early days of radio transmission. Many a schoolchild made a "bits and pieces" receiver with the silver foil from a bar of chocolate, a thimble, a cardboard roll, some wire and a crystal costing a few pennies.

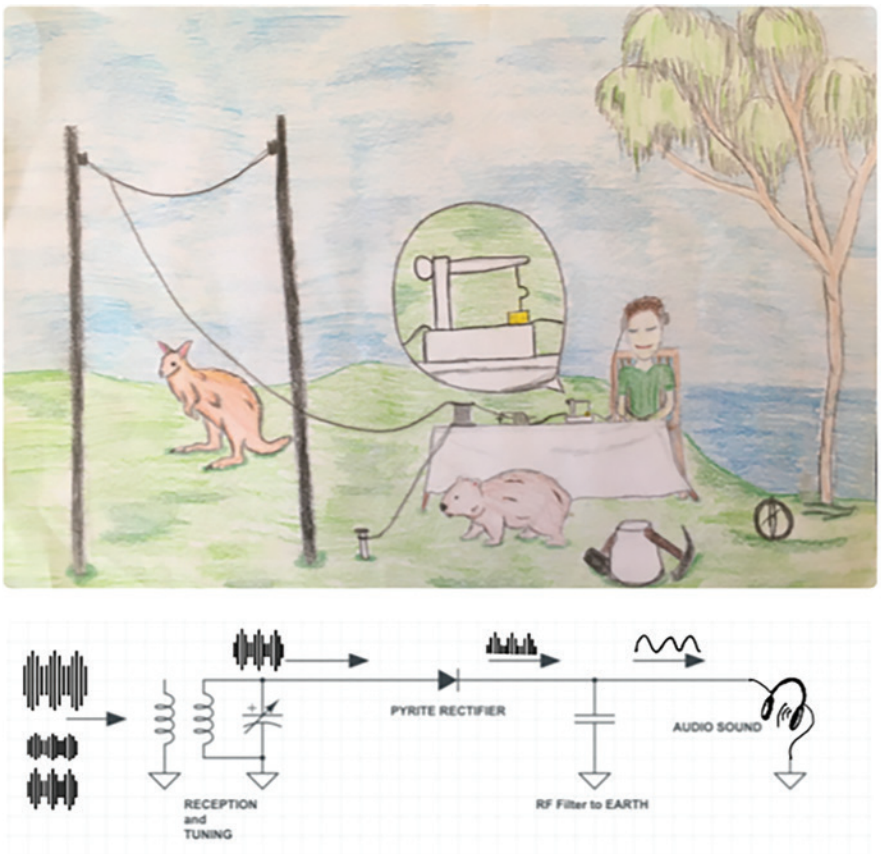

Figure 9. *Communications were vital in the early days of geophysical prospecting. Here, in this depiction of a base camp, lakeside in the outback, intrepid party leader Ashley, after a bush tucker breakfast, was able to receive instructions from head office and, by rotating the tuning capacitor, could catch news broadcasts, or soothing music, before facing the rigours of the exploration day. This environmentally friendly technology depended on the pyrite detector. A yellow piece of rectifying pyrite crystal (see inset) is held in a cat's whisker jig. Polluting fossil fuel power was not required. On the ground, between the bucket and the tree, is one of the instruments of the day: a dip-needle (see Heiland 1940), which, when properly compensated and oriented, indicates changes in vertical magnetic intensity along Ashley's traverse lines (note that the name Ashley is gender neutral.*

In the tapped coil, variable capacitor, primitive radio receiver, the cat's whisker crystal detector could be galena, but pyrite was better with regard to: easy placement of the cat's whisker, withstanding ambient conditions, continuity of sensitivity over long periods, and tonal purity in reception. However, apparently, only certain limited types of pyrite were suitable, so galena was more frequently used. The exploration relevance or significance of asymmetric current conduction, or diode effect, in natural sulphide types, would seem to warrant some study.

Pyrite – conductivity

Samples

There is a considerable spread of conductivity values reported for pyrite, 1 to 100 000 S/m (Shuey 1975). To contribute to understanding better pyrite's electrical characteristics, opportunity was taken to carry out conductivity measurements on the suite of 36 pyritics listed in Table 3 in the following ten categories: large single crystal (#1–4), massive medium to coarse grained low porosity aggregate (#5–10, 36-nodular), high porosity aggregate (#11–15), high alteration (#9), massive very finely crystalline with minor silicates and other sulphides (#16–19), massive with minor pyrrhotite and other sulphides (#20–23), minor pyrite-networked veinlet (#25, 26), fine grained banded (#27–33), fine grained banded with minor chalcopyrite (#24, 34, 35). The pyrite in all the samples is networked i.e. there is electrical continuity through the core or across the core in the case of banded samples drilled normal to foliation to give maximum flux coupling in the EM energisation producing eddy currents around the core. Disseminated pyritics with grains or clusters of grains electrically isolated from one another were not included in the sample suite for reasons given below.

Measurements

Laboratory mesoscale measurements were carried out on cored, or shaped, air-dried samples for electrical conductivity and magnetic susceptibility. Induction coils were used and energised to 1 MHz for induced electromagnetic conductivity and 400 Hz for magnetic susceptibility. Changes in the resistance (R) and inductance (L), when cores were inserted, were measured by an RCL metre. Following Yang and Emerson (1997) conductivity was determined from ΔR, and susceptibility from ΔL. Mass properties were measured, following Emerson (1990), so that the conductivity data could be viewed in the perspective of density. Although the writer has carried out many galvanic measurements on pyritics, EM conductivity was the preferred technique here. The EM measurement (Figure 10) is not responsive to insulating minerals, it just "sees" conductors and induces eddy currents in them; also it is quicker to do. Lab EM favours conductive features normal to the core axis; galvanics, parallel to the core axis. The differences, which do exist for banded pyritics, are related to texture and will not be dealt with here where only maximum conductivities are presented and plotted. Auxiliary four electrode DC galvanic measurements were made to check some of the EM measurements, and two electrode galvanic microprobing was also undertaken in investigating alteration films and pockets.

Disseminated pyrite is not included in the test suite. Such pyrite, dispersed and disconnected in a resistive matrix, is not suitable for measurement by EM induction. The conductivity (σ) of such a mix would be quite low. It is best addressed by galvanic methods and modelled by a mixing law such as a modified Maxwell's equation. For dispersed conductive spheres, one approximate version of this equation is (Shuey 1975):

$$\sigma_{mix} = [(1+2p)/(1-p)]\ \sigma_m$$

where p is the volume percent of porphyritic metallic, σ_m is the conductivity of the continuous, insulating matrix, and σ_p the conductivity of the dispersed metallic is assumed to be many orders of magnitude greater than σ_m (so it does not appear in the equation). For $\sigma_m = 10^{-3}$ S/m, p = 10%, the overall conductivity of the mix is 0.0013 S/m (–> 752 ohm m res.) barely above the matrix, as one would expect. But in EM testing of such material, a response is obtained from small eddy current loops confined to individual particles and not from eddy currents circulating around the entire core. This gives a pseudo-conductivity dependent on particle conductivity, concentration, diameter and the core diameter (Yang and Emerson 1997). Here the measured conductivity is:

$$\sigma_a = p\ \sigma_p\ (d/D)^2$$

where σ_p is the conductive particle conductivity, d the particle diameter, and D the core diameter. For 10% crystal pyrite, σ_p = 4000 S/m (say), d = 1mm, D = 25.4mm core, then σ_a = 0.62 S/m – quite a different result, but of no use in establishing the actual conductivity of the core. However, the equation is useful in gauging the conductivity of the particles if σ_a, p, d, and D are known. [This effect is quite pronounced in the case of native copper platelets or crystals, set in a resistive matrix, owing to copper's extremely high conductivity, ~60 x 10^6 S/m.] Any inductively measured sample suspected of isolated metallic particle behaviour should first be tested with a galvanic two electrode ohm probe to establish sulphide electrical continuity over the entire core, or in bands in the core (i.e. is the sulphide networked?). If the sulphide particles are completely isolated electrically then all that the test core induction coil EM response tells the geophysicist is that there are sulphides or other conductors disseminated in the core.

Another pitfall is worthy of mention. Core testing by the EM conductivity method for conductivities upwards of a few 100s mS/m, is convenient and fast. However, on no account should a core be held by the fingers in any induction coil as the coil will couple to the fingers through the core. The fingers of a human hand have a conductivity of a few S/m, so a resistive core will show a quite spurious conductivity. Although this does not matter too much for a very conductive core e.g. massive pyrrhotite, it is good practice, if a core has to be held in a coil, to use plastic tongs. In using a short coil to scan long lengths of benched core, hands-off measurement is essential.

Results

The mass property, magnetic susceptibility, and EM conductivity data are given in Table 3. Ward (1966) defines a massive sulphide as being at least 50% by volume sulphides and having a minimum density of 3.8 g/cc. However, for this 36 sample data set it is deemed preferable to classify the 25 samples with air dried bulk densities exceeding 4.2g/cc as massive, the five samples (#28–31, 35) with densities in the 3.7–4.0 g/cc range as semi massive, and the remaining six samples (#25–27, 32–34) in the 2.7–3.3 g/cc range as low density pyrite rock. Half the samples tested have inferred grain densities in excess of 4.6 g/cc attesting to their heavily pyritic nature. The presence of minor amounts of sulphate alteration, silicates, and sulphides such as sphalerite, will result in densities below the nominal 5.0 g/cc

Table 3. Pyrite conductivity data:

#	BD g/cc	mag k SI x 10^{-5}	EM cond. S/m	DBD g/cc	WDB g/cc	P_A %	GDA g/cc
1	4.96	2	2050	4.96	4.97	1.2	5.02
2	4.93	2	1857	4.93	4.94	1.1	4.99
3	4.86	2	4250	4.86	4.86	< 0.1	4.86
4	4.92	2	4630	4.92	4.92	< 0.1	4.92
5	4.96	3	116	4.97	4.98	0.7	5.01
6	4.89	2	35	4.88	4.90	1.8	4.97
7	4.90	2	54	4.90	4.91	1.6	4.98
8	5.00	2	186	5.00	5.00	0.3	5.00
9	5.02	2	88	5.02	5.02	0.2	5.02
10	4.82	2	28	4.82	4.85	2.8	4.96
11	4.73	2	59	4.72	4.79	5.6	5.00
12	4.53	2	34	4.52	4.58	5.8	4.81
13	4.31	2	17	4.61	4.42	12.1	4.89
14	4.40	2	20	4.38	4.47	9.2	4.82
15	4.60	2	45	4.57	4.65	7.7	4.95
16	4.82	2	15	4.81	4.81	< 0.1	4.81
17	4.61	50	11	4.60	4.63	1.9	4.69
18	4.30	38	6	4.30	4.33	3.0	4.43
19	4.60	1	4.2	4.60	4.61	1.0	4.65
20	4.39	820	80	4.39	4.46	2.9	4.52
21	4.27	491	89	4.27	4.27	< 0.1	4.27
22	4.23	416	69	4.23	4.23	0.3	4.24
23	4.47	452	108	4.47	4.47	< 0.1	4.47
24	4.50	8	78	4.50	4.50	0.2	4.51
25	2.80	12	0.7	2.80	2.80	0.5	2.81
26	2.75	4	0.5	2.75	2.75	0.3	2.76
27	3.12	23	1.1	3.12	3.13	0.8	3.15
28	3.73	4	2.5	3.73	3.73	0.2	3.74
29	3.81	25	2.3	3.81	3.81	< 0.1	3.81
30	3.99	31	2.8	3.99	3.99	0.3	4.00
31	3.90	27	1.5	3.90	3.91	1.0	3.94
32	3.29	21	0.6	3.29	3.30	0.5	3.31
33	3.05	43	0.7	3.05	3.05	0.3	3.06
34	3.23	44	3.5	3.23	3.23	< 0.1	3.23
35	3.83	25	16	3.83	3.83	< 0.1	3.83
36	4.77	4	8	4.76	4.77	0.5	4.78

Notes:

- *BD – bulk density air dried, as collected; DBD – dry bulk density, 105° dried; WBD – freshwater saturated density; P_A – apparent (water accessible) porosity; GDA – inferred grain density; measurements made @ 22°C temperature.*
- *Magnetic susceptibility, mag k, measures in an induction coil @ 400 Hz.*
- *Electromagnetic conductivity, EMσ, measured in an induction coil energised to 1 MHz or below onset of skin effect frequency, EM cond. values ≥10 S/m rounded off. The EM conductivity is deemed to be a quasi- DC conductivity. The high frequencies are required for a good signal to noise ratio as, pursuant to Faraday's Law, the magnitude of the induced electromotive force in a conducting loop of material equals the magnitude of the rate of change of flux through it.*
- *EM conductivity max. measured value given: for a banded sample this is parallel to bedding where energising flux in ind. coil is normal to bedding; some banded samples have silica or silicates between pyrite layers and conductivity normal to bedding is quite low, in such cases the cited conductivity would be apparent as it is only due to the conductive part of the core.*
- *Measurement accuracy better than 1%, measurements are mesoscale, air dried state. Coil measurements made with Rhodes & Schwarz HM 8118 bridge and Fluke PM 6306 RCL meter.*
- *Sample locations: #1, 2 Arusha region Tanzania; #3, 4 Navajùn, Spain; #5-9, 11-13, 15 Dos de Mayo province Peru; #10, 14 Gumeracha Sth Australia; #16, 17, 20 Elura NSW Palaeozoic; #18 Mt Lyell, Tasmania; #19, 28, 33 Kalgoorlie region Precambian greenstones Western Australia; #21, 24, 27, 29, 30, 34, 35, Mt Isa Group, Queensland; #22, 23 Woodlawn NSW Palaeozoic; #31 Porgera, Pacific Islands; #32 McArthur Basin Group, Northern Territory; #36 nodular pyrite, Hunan Province, China; total of 36 locations, all hard rock terrain – soft rock sedimentary pyrite not included in sample suite.*

for pure pyrite. The cube specimen #3 has a low grain density for pyrite, 4.86 g/cc, which is assumed to be due to internal occluded voids inaccessible to the vacuum saturant.

Porosities are very low (≤0.1%) for eight samples, low (0.2–0.8%) for twelve samples, moderate (1–2.9%) for ten samples, high (5.6–12.1%) for five Peruvian samples (very voidy, visually), and very high (22.9%) for an extremely weathered massive (now skeletal) sulphide (#19).

Magnetic volume susceptibilities (k) are generally low ($\leq 50 \times 10^{-5}$SI) except for four samples (#20–23) containing minor pyrrhotite ($416–820 \times 10^{-5}$SI). Pyrite's mag k was thought to be $\sim 4 \times 10^{-5}$SI, but 16 samples have mag k values below this. Sample mag k's up to 50×10^{-5}SI can be ascribed to the presence of minor amounts of Fe paramagnetic silicates, Fe carbonate etc.

The conductivity data are best viewed in the perspective of a density crossplot which is presented in Figure 11 where the sample conductivities from low (0.5 S/m) to high (4250 S/m) are clearly seen to increase, broadly with density.

Interpretation

The data have been grouped and trended as follows:

I. massive single crystal pyrite, #1, 2, 3, 4;
II. massive variably porous pyrite, polycrystalline aggregate, #5–15;
III. massive pyrite + minor silicate and sphalerite in siltstone, #16, 17;
IV. pyrite altered-minor alt. #36, moderate alt. #19;
V. pyritic banded metasediment, moderately pyritic to semi massive, #27–33;
VI. veinlet, blebby pyrite in black shale, #25, and quartz #26;
VII. banded, #34, semi massive, #35, and massive, #24, pyrite all with minor chalcopyrite;
VIII. massive pyrite with minor pyrrhotite, #20–23 (note the elevated mag k values in Table 3).

Also shown are chalcopyrite ore with metasedimentary gangue, C, Cobar NSW; and nickeliferous pyrrhotite, K, from Kambalda WA. These two massive sulphide samples contain minor pyrite and are not in Table 3, they are included for comparison only, to contrast with the lower conductivity of massive polycrystalline pyrite.

The pyrite single crystal conductivities (i) are high by any standard, 1000s S/m. However, pyrite of interest in the field occurs massively aggregated and the conductivities of the samples (ii, iii) in this group are two orders of magnitude below that of the single crystals. Conductivities in the 10s to low 100s S/m increase, more or less, with density and diminishing porosity. Voids, microcracking, intercrystalline alteration products, and grain boundary replacement (surface film) of presumably Fe sulphate and/or marcasite (Deer, Howie, and Zussman 1992) can be seen or presumed in the samples. All serve to reduce conductivity and this tendency is exacerbated by pyrite's cubic blocky crystallinity. So texture, overall, impedes aggregated pyrite attaining its single crystal conductivity, at least in the samples tested here. Contrast this with the pervasive, threading, connecting, dendritic habit of chalcopyrite and pyrrhotite, much better for electrical continuity than sutured pyrite polyhedra.

Minor amounts of insulating minerals diminish conductivity (iii); alteration of the pyrite lowers conductivity yet further (iv).

Figure 10. *Coarse grained Gumeracha pyrite from South Australia provided the core for testing in an induction coil of type used in the conductivity measurements. The wire winding is 70 mm long x 30 mm internal diameter. A conductive core inserted in the coil causes a change in its resistance, ΔR, which is measured on an LCR meter. If the core is magnetic it also causes a change in the coil inductance, ΔL. From these quantities electromagnetic conductivity and magnetic susceptibility are derived (Yang and Emerson 1997). The measurements are usually run in the kHz range (below the onset of skin effect). An air gap correction would be necessary if this method is used for a mag k measurement. For low susceptibility pyrite the change in inductance is quite small so a high sensitivity meter is required. The 45 mm long, 25 mm diameter Gumeracha pyrite test core shown here is sample 10 with a 28 S/m EM conductivity and 2×10^{-5} SI mag k. This pyrite is porous and has a minor silicate content.*

Adding minor chalcopyrite to the pyrite boosts conductivity (vii), as does minor pyrrhotite (viii) which is even more effective.

The remaining pyritic categories (v), (vi) have quite low conductivities around the 1 S/m level. These conductivities are apparent as they are due to bands in the core not to the whole core.

Typical massive chalcopyrite ore (C) has a conductivity comparable to single crystal pyrite; the massive nickeliferous pyrrhotite (K) is an order of magnitude better.

The groupings are based on mineralogy and texture, but the superimposed trends are subjective. No claims whatsoever are made for the data being generally definitive of pyrite, but the data are indicative of at least some types of pyrite conductivity and pyrite's frequent inferiority to chalcopyrite and pyrrhotite.

Marcasite

Marcasite is the low temperature, chemically unstable, orthorhombic dimorph of pyrite. It can be difficult to distinguish from pyrite, sometimes Xray diffraction is required. It has a pale yellow colour, its density, 4.89 g/cc, is less than that of pyrite, 5.02 g/cc. It deteriorates rapidly in moist air and many a mineral collection cabinet has been ruined by its ferrous sulphate and sulphuric acid alteration products. Usually the presence of white

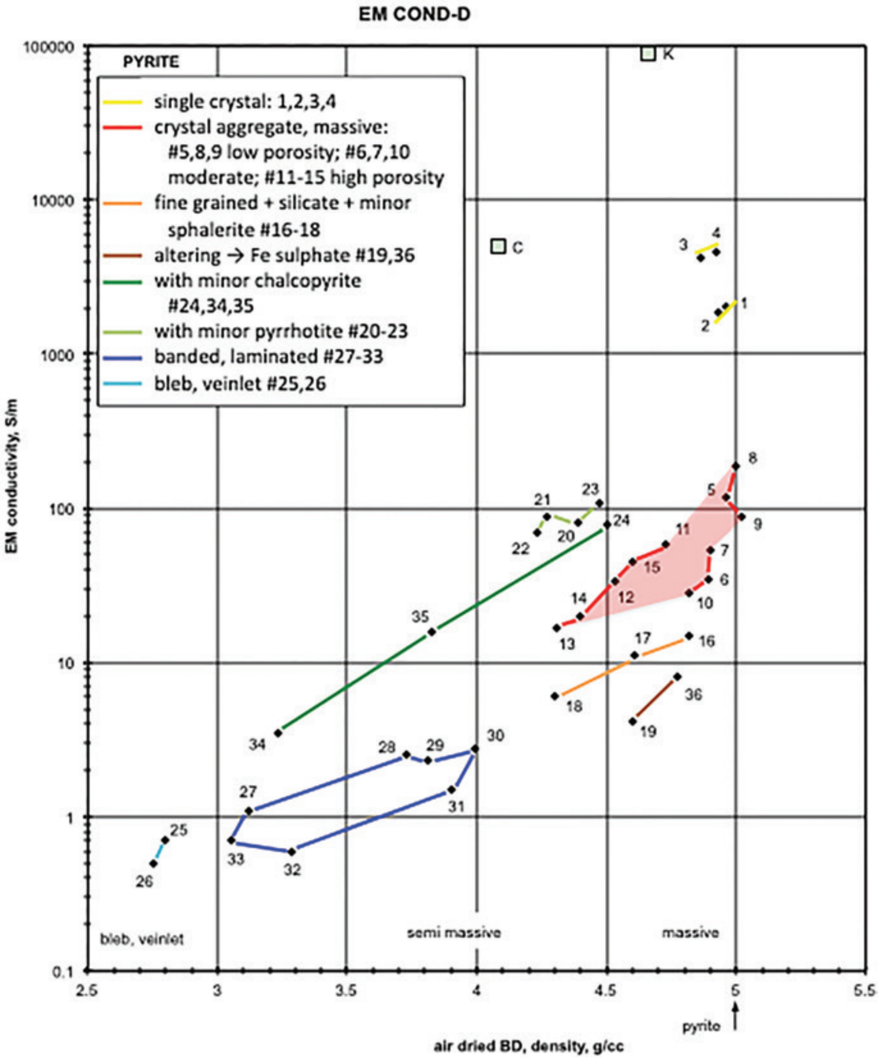

Figure 11. *Crossplot of air dried values of EM conductivity and bulk density for the 36 pyritic samples in Table 3. Overall, conductivity increases with density. Single crystal conductivities are quite high (1000's S/m) and exceed the modal value for n type pyrite (1000 S/m; Shuey 1975). Aggregated pyrite in massive form has a diminished conductivity (10's to 100's S/m) owing to grain boundary and other effects. The massive fresh pyrite set (#5–15) is shown in three groups one of which with high porosity (#11–15) matches the low porosity trend (#6, 7, 10) in conductivity presumably because of better grain to grain suturing. Conductivity in the massive types is reduced by the presence of minor sphalerite and silicates (#16–18) and still further by alteration (#19, 36). Banded and blebby pyritic metasediments have quite low conductivities (few S/m, or less). Minor chalcopyrite content (#24, 34, 35) boosts pyrite conductivity, and even more so does minor pyrrhotite (#20–23). The red shaded area suggests a range of conductivity that may be encountered in massive, variably porous pyrite devoid of chalcopyrite and pyrrhotite. Pyrite, apart from the single crystals, is not very conductive, at least in the set of samples documented here. Included for comparison are a massive chalcopyrite (C) from siltstones of the Cobar Group NSW and a massive pyrrhotite (K) from an ultramafic environment at Kambalda WA. Both are significantly more conductive than the massive pyrite tested here. The pyrite data are deemed instructive and indicative, but by no means definitive of all varieties of pyrite.*

powdery melanterite, $FeS0_4 \cdot 7H_20$, on grain boundaries and in cracks, together with an acrid smell will serve to identify it. In limited measurements the writer carried out on clearly altering material, conductivity seems to be of the order of a few S/m, Harvey (1928) measured three samples with conductivities ranging from 10 to 1000 S/m, presumably on fresh polished surfaces. Unfortunately fresh unaltered marcasite could not be located to include in the measurements made for this article.

Concluding remarks

A blend of tough iron and soft sulphur could be expected to yield an interesting substance. The covalent chemical combination, as a disulphide, of these two disparate elements does not disappoint. For humankind pyrite has been, and continues to be, a very significant mineral because of its involvement in, and contributions to, culture, industry, materials science, geoscience, and, indeed, to life itself. It has been an impressive set of physical properties which merit appreciation, and it warrants continuing study, especially as to its electrical properties. Pyrite, the firestone, historically and currently is a very important mineral. Pyrite matters. It is advantageous for geoscientists to know if it is about, for one reason or another, for better or for worse.

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Don Emerson is a geophysical consultant specialising in the physics of minerals and rocks, he also has an interest in ancient and medieval geoscience.

Preview crossword #5

Across	Down
1. A term used in remote sensing techniques to describe the display of data collected in a number of different wavelengths, usually longer or shorter than those perceptible to the naked eye	**2.** An instrument which measures gamma radiation
5. The point in the orbit of the moon or any artificial satellite that is most distant from the Earth	**3.** Section of a river channel that no longer carries the main discharge. Its abandonment results from meander development associated with lateral channel migration across a floodplain.
8. A naturally occurring electrical current which flows at or near the Earth's surface over very large areas	**4.** An anticyclonic storm system in the atmosphere of the southern hemisphere of Jupiter that has been observed for more than 300 years
10. A mathematical model in which only one boundary exists, all others being infinitely far away	**6.** An iron and nickel sulphide, and the main ore mineral for nickel
11. A group of extinct molluscs named after the Egyptian deity Ammon, who was often depicted wearing coiled ram's horns	**7.** Applied to a crystal system where the Bravais lattices have three sets of edges at right angles, but all are of different lengths
13. The only known moon in the solar system with an atmosphere	**9.** A variety of quartz produced at very high pressures and found in rocks subjected to impact by large meteorites
14. The angle between magnetic North and true geographic North	**12.** A city in Germany where pendulum instruments were used to measure the absolute value of gravity acceleration, which led to the first gravity datum that was eventually used to expand into a system of worldwide network of stations tied to this city

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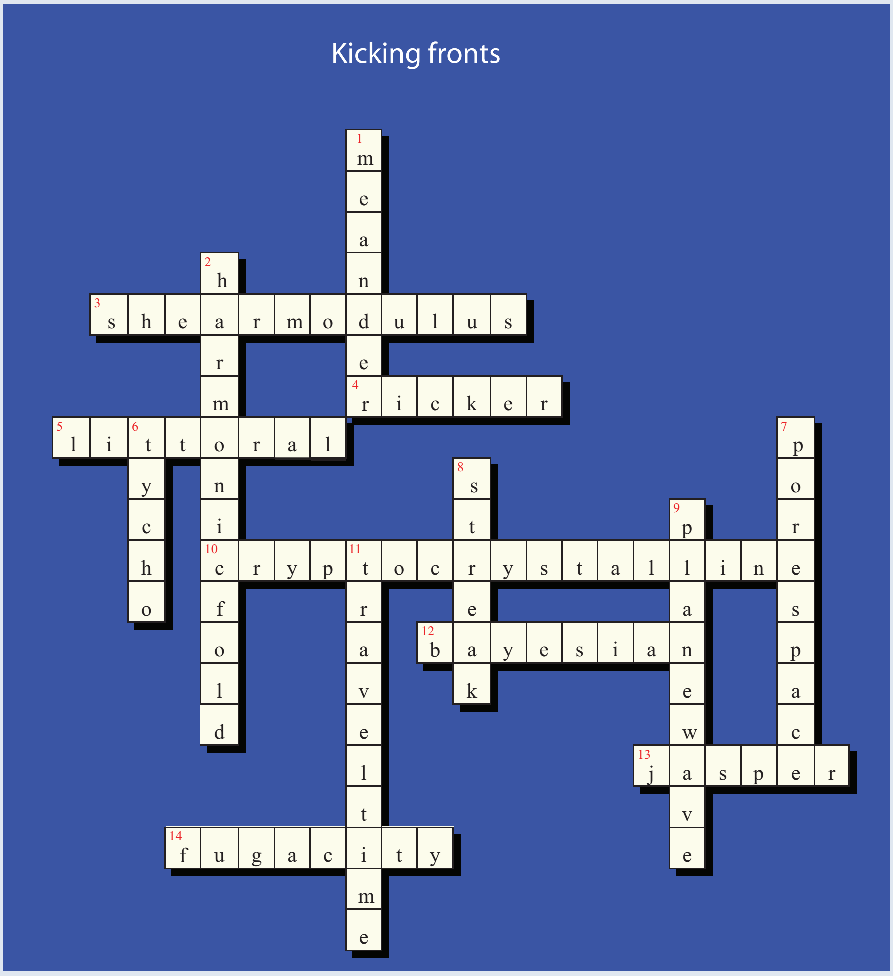

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5	Tasmania Geoscience Forum https://ausimm.com/news/registrations-now-open-tasmania-branch-geoscience-forum-2019/	Hobart	Australia
9–13	American Geophysical Union Fall Meeting https://www2.agu.org/fall-meeting	San Francisco	USA
10–12	SEG | EAGE Workshop: Geophysical Aspects of Smart Cities https://seg.org/Events/SmartCitySingapore	Singapore	Singapore
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12–14	AGS Workshop on InSAR and its Application for Understanding Ground Movement https://australiangeomechanics.org/courses/ags-tasmania-radar-interferometry-workshop/	Hobart	Tasmania
23–25	SPG 13th Biennial Conference & Exposition https://www.spgindia.org/forthcoming-conferences	Kochi	India
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March	**2020**		
3–8	36th International Geological Congress https://www.36igc.org/	New Delhi	India
11–16	SEG International Exposition and 90th Annual Meeting	Houston	USA
15–20	International Symposium on Deep Seismic Profiling of the Continents and their Margins (SEISMIX 2020) http://www.seismix2020.org.au	Fremantle	Australia
23–26	DGG 80th Annual Meeting https://dgg2020.dgg-tagung.de/englisch/	Munich	Germany
24–27	Offshore Technology Conference Asia (OTC Asia) http://2020.otcasia.org/welcome	Kuala Lumpur	Malaysia
29–2 April	Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP) https://www.sageep.org/	Denver	USA
April	**2020**		
19–21	AI Earth Exploration Workshop: Teaching the Machine How to Characterize the Subsurface https://seg.org/Events/Artificially-Intelligent-Earth-Exploration	Muscat	Oman
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May	**2020**		
3–8	European Geosciences Union https://www.egu2020.eu/	Vienna	Austria
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